Agent-based Modelling of Transitions towards Sustainable Construction Material Management: The Case of Switzerland

Dissertation

zur

Erlangung der naturwissenschaftlichen Doktorwürde
(Dr. sc. nat.)

vorgelegt der

Mathematisch-naturwissenschaftlichen Fakultät

der

Universität Zürich

von

Christof Knöri

von

Zweisimmen, BE

Promotionskomitee
Prof. Dr. Claudia R. Binder (Leitung der Dissertation)
Dr. Hans-Jörg Althaus
Prof. Dr. Michael Schaepman (Vorsitz)

Zürich, 2015

Summary

Problem: A transition towards sustainable construction materials management presents one of the bigger challenges of the 21st century, with construction materials among the most heavily consumed commodities globally and increasing construction & demolition (C&D) waste streams. Thus, reusing C&D waste as recycled mineral construction materials (RMCM) has been considered as a potential solution. However, despite proven and standardised technical feasibility RMCM are not yet broadly accepted and environmental benefits of RMCM compared to conventional materials were still unclear. Therefore a better understanding of supply and demand of RMCM and respective environmental implications was necessary.

Goals: This research aimed to fill this gap by developing an agent-based model to simulate socio-technical transitions towards a more closed-loop construction material management, and on this basis, provide recommendations for sustainable construction material management.

Methods: These goals were addressed by the means of the Swiss construction material case study. The research was structured in four modules, (i) a material flow model of potential RMCM supply, (ii) an empirical operationalization of actors' decisions and interaction regarding the demand for RMCM, (iii) an agent-based socio-technical model integrating supply and demand, and (iv) a life-cycle assessment (LCA) of RMCMs' environmental impacts.

Results: The agent operationalization approach was developed to provide a comprehensive framework to empirically operationalize key system agents, their interaction, decision-making and behaviour and thus addressing major shortcomings limiting an exploitation of ABM's full potential.

Reusing C&D waste for RMCM showed a significant supply potential, where up to 40% of the natural aggregates in structural engineering (SE) could be substituted. Despite this potential, construction stakeholders in SE still mainly preferred conventional materials in contrast to their colleagues in civil engineering where RMCM was an accepted option.

Two factors were key to enhance the demand for RMCM in SE: first extensive information campaigns as RMCM were not considered as an option on a regular basis, and second linking initial sustainable construction specifications with RMCM. The scenario analysis showed that information campaigns together with small price incentives could increase the demand up to 70% of all RMCM applications and consequently about 50% of expected C&D waste volumes could be reused.

The environmental impacts assessment demonstrated clear benefits (about 30%) for recycled concrete compared to conventional concrete, mainly originating from avoided pig-iron production and C&D waste disposal, and stand as long as additional amount of cement and transport distances for RC are limited. Applying these results to the simulation outcomes revealed a possible total environmental impact reduction from the concrete production in

Switzerland of approximately 20%. Therefore, C&D waste reuse for RMCM present a valuable transition pathway toward a more sustainable construction material management.

Conclusion: This research achieved an in-depth understanding of construction stakeholders' demand patterns for RMCM depending on potential supply of RMCM, and revealed environmental implications of transitions towards closed-loop construction material management. It also contributed to the methodological development by developing the agent-operationalization approach, providing a context specific agent-based model of a socio-technical transition, and integrating agent-based modelling and life cycle assessment.

Zusammenfassung

Problemstellung: Nachhaltiges Baustoffmanagement ist sowohl aus der Ressourcen- wie auch aus der Abfallperspektive zentral für das Funktionieren westlicher Gesellschaften. In Industrienationen gehören Baumaterialien zu den meist konsumierten Gütern und Bauabfall zu den größten Abfallströmen. Diese Verhältnisse scheinen sich in Zukunft aufgrund ansteigender Bevölkerungszahlen, verdichteter Bauweise und knapper werdenden Deponievolumen noch zu verschärfen. Als Lösung wird vermehrt die Wiederaufbereitung von mineralischem Bauabfall zu Recyclinggranulat zur Substitution von natürlichem Sand und Kies diskutiert. Obwohl das Angebot an Sekundärbaustoffen, die Normierung dieser Baustoffe und die Errichtung von Referenzobjekten für deren Einsatz sprechen, ziehen Bauakteure in der Schweiz - insbesondere im Hochbau - mehrheitlich konventionelle Baustoffe vor. Darüberhinaus werden auch die ökologischen Vorteile von Sekundärbaustoffen im Vergleich zu konventionellen Baustoffen in Frage gestellt. Ein besseres Verständnis von Angebot und Nachfrage nach Sekundärbaustoffen sowie deren Umweltauswirkungen sind daher erforderlich.

Ziele: Das Ziel dieser Forschungsarbeit war die Entwicklung eines agentenbasierten sozio-technischen Modells zur Simulation von Transformationsprozessen hin zu geschlossenen Stoffkreisläufen und daraus Empfehlungen für ein nachhaltiges Baustoffmanagement abzuleiten.

Methoden: Der Schweizer Baustoffmarkt hat als Fallstudie gedient, um diese Ziele anzugehen. Das Forschungsvorhaben wurde in folgende vier Analysemodule aufgeteilt: (i) ein Materialflussmodul zur Bestimmung des potentiellen Angebots an Sekundärbaustoffen, (ii) ein Modul zur empirischen Operationalisierung von Akteuren, deren Interaktion und Entscheidungen hinsichtlich der Nachfrage nach Sekundärbaustoffen, (iii) ein Modul für ein agentenbasiertes sozio-technisches Modell zur Integration von Angebot und Nachfrage, sowie (iv) ein Modul zur Beurteilung der Umweltauswirkungen.

Ergebnisse: Der „Agenten-Operationalisierungansatz“ kombiniert partizipative und sozialwissenschaftliche Methoden, um Akteure sowie deren Interaktionen und Entscheidungsprozesse empirisch zu bestimmen und einfach in kontextspezifische Modelle zu integrieren. Somit geht dieser Ansatz wichtige Kritikpunkte der agentenbasierten Modellierung (ABM) an, welche bisher eine volle Ausschöpfung des Potentials der Methode verhindert haben.

Die Wiederverwertung von Bauabfall in Sekundärbaustoffen hat in der Schweiz großes Potential. So könnte zum Beispiel bis zu 40% der heutigen Kies- und Sandnachfrage für die Betonproduktion im Hochbau durch Recyclingaggregate substituiert werden. Trotz dieses potentiellen Angebots liegt die Nachfrage nach Sekundärbaustoffen im Hochbau bei nur 11% und Bauakteure ziehen mehrheitlich konventionelle Baustoffe vor. Anders im Tiefbau, wo Sekundärbaustoffe mit einem Marktanteil von über 30% bereits gut etabliert sind.

Sensitivitätsanalysen haben gezeigt, dass weniger die Entscheidungskriterien oder deren Gewichtung, sondern vielmehr die Bekanntheit von Recyclingbeton für die Nachfrage zentral ist, welcher bisher nicht standardmäßig als Entscheidungsoption berücksichtigt wurde. Insbesondere ist eine Assoziation von nachhaltigem Bauen mit Rückbaustoffen bei Architekten und Ingenieuren entscheidend. Durch konsequentes Informieren der Bauakteure ließe sich im Hochbau längerfristig die Nachfrage nach Recyclingbeton von momentan 11% auf rund 50% (und bis zu 70% in Kombination mit Preisvorteilen) steigern. Dadurch könnten im Hochbau der gesamte Betonabbruch sowie rund 50% des Mischabbruchs wiederverwertet werden.

Die Ökobilanzierung hat gezeigt, dass die Umweltauswirkungen von Recyclingbeton um bis zu 30% geringer sind als die von konventionellem Beton. Dieser Unterschied kann hauptsächlich durch den Umweltnutzen aus der Vermeidung von Entsorgungsprozessen und der Rückgewinnung von Armierungsstahl, welcher durch die Produktion von Recyclingbeton verursacht wird, erklärt werden. Solange die zusätzlichen Transportdistanzen für Recyclingbeton nicht weiter als 15km und dessen Mehrzementbedarf nicht über 10% liegt, bleibt Recyclingbeton umweltfreundlicher als konventioneller Beton. Werden diese Resultate mit denen des sozio-technischen Modells kombiniert, so zeigt sich, dass die gesamte durch die Betonproduktion verursachte Umweltbelastung um rund 20% gesenkt werden könnte. Daher lässt sich ableiten, dass die Wiederverwertung von Bauabfall in Sekundärbaustoffen einen wertvollen Entwicklungspfad hin zu nachhaltigem Baustoffmanagement darstellt.

Schlussfolgerungen: Mit dieser Dissertation ist ein vertieftes Verständnis von Entscheidungs- und Verhaltensdynamiken von Bauakteuren hinsichtlich der Nachfrage nach Sekundärbaustoffen und den potentiellen Umweltauswirkungen von Transformationsprozessen hin zu geschlossenen Stoffkreisläufen geschaffen worden. Darüberhinaus konnte ein methodischer Beitrag geleistet werden. Einerseits durch die Entwicklung des „Agenten-Operationalisierungansatz“ und eines kontextspezifischen, agentenbasierten Modells zur Simulation von sozio-technischen Transformationsprozessen. Anderseits durch die Verknüpfung von agentenbasierter Modellierung und Ökobilanzierung.

Table of contents

Part A – Synopsis

1 Introduction

1.1 Sustainable construction material management

A transition towards sustainable construction materials management presents one of the bigger challenges of the 21st century, with construction materials among the most heavily consumed commodities globally, increasing construction & demolition (C&D) waste streams, and consequently significant environmental impacts.

Firstly, concrete is the most heavily consumed material in the construction sector and the second most heavily consumed substance on Earth after water (Weil, Jeske, & Schebek, 2006). The estimated worldwide concrete consumption was between 21 and 31 billion tonnes in 2006 (WBCDS, 2009). This increasingly puts pressure on natural gravel recourses, and although they are often considered as abundant, it will potentially increase conflicts with alternative uses (i.e. nature reserve areas, groundwater protection, flood protection, and renaturation projects) (Kind, Müller, Vogt, & Suter, 2006; Redle, 1999).

Secondly, C&D waste already comprises the largest waste fraction in industrialized countries (Schachermayer, Lahner, & Brunner, 2000), and is expected to increase in the future. Studies from the Netherlands (Muller, 2006) and Norway (Bergsdal, Brattebo, Bohne, & Mueller, 2007) show this trend for countries of the European Union, Hashimoto et al. (2007) for Japan and Hao et al. (2007) for Hong Kong.

These vast and increasing material streams do not come without ecological consequences. For example the carbon footprint from cement production is estimated to account for about 5% of the global carbon emissions (Huntzinger & Eatmon, 2009; van Oss & Padovani, 2003; Worrell, Price, Martin, Hendriks, & Meida, 2001). Further, environmental impacts from C&D waste disposal are starting to accumulate although C&D waste contains mostly inert materials (Doka, 2007; Hashimoto et al., 2007; Weil et al., 2006).

To address both of these issues, C&D waste reuse as aggregate substitutes for concrete or roads aggregates has been considered as a valuable option to:

- substitute primary aggregates (Blum & Stutzriemer, 2007; Rao, Jha, & Misra, 2007; Weil et al., 2006),
- reduce the C&D waste deposition (Hiete, Stengel, Ludwig, & Schultmann, 2011; Lawson et al., 2001; Woodward & Duffy, 2011), where space for landfills is increasingly scarce (Duran, Lenihan, & O'Regan, 2006; WBCDS, 2009), and to
- reduce associated environmental impacts (Fatta et al., 2003; Jang & Townsend, 2001).

1.2 C&D waste reuse for recycled mineral construction materials (RMCM)

Three general issues relate to the reuse of C&D waste to substitute aggregates in recycled mineral construction materials (RMCM): material flow, acceptance, and ecological issues.

1.2.1 Material flow issues

In Switzerland, the already large amounts of C&D waste (i.e. about 11 million tons in 1997) are likely to increase because of the increasing requirements of housing space per capita and the decreasing availability of construction land, leading to increased demolition of old buildings (FOEN, 2004). Depending on the construction scenario, expected volumes of C&D waste per year in 2050 range from 20 to 65 million tons (Moser, Bertschinger, Hugener, Richner, & Richter, 2004). However, about 80% of the C&D waste is currently recycled (FSO, 2010). This comparably high recycling rate is mainly due to high on-site recycling rates in civil engineering (CE), where about 94% of the C&D waste is reused (FOEN, 2001a, 2005). C&D waste from structural engineering (SE) is usually down-cycled (i.e. used in low-grade applications such as lean concrete) or landfilled (FOEN, 2001a; Spoerri, Lang, Binder, & Scholz, 2009). Recycling on the same application level, e.g. recycling concrete into high-grade concrete, covers just 1.7 million tons out of 9 million tons RMCM per year (FOEN, 2004). With an expected decrease in construction activity in CE and increasing C&D waste streams from SE, down-cycling will not be sufficient to maintain the overall recycling rate and thus, more closed loop recycling might be required.

1.2.2 Acceptance issues

Recycled concrete (RC) presents one such closed loop recycling option for C&D waste streams from SE. Although properties of RC differ slightly from conventional concrete the technical potential of using RC for structural concrete applications has been demonstrated in various research projects (Hoffmann & Jacobs, 2007; Li, 2008; Poon, Kou, Wan, & Etxeberria, 2009; Rao et al., 2007). In addition, these applications have already been incorporated in legislation and standards (FOEN, 2006; KBOB, 2007; SIA, 2010) and reference projects have demonstrated their practicability (Hofmann & Patt, 2006). However, even though RMCM are technically feasible, regulated, and successful application examples are available; they are not yet broadly applied in Switzerland. This has been related to construction stakeholders' lack of acceptance of RMCM and their clear preferences for conventional materials (Moser et al., 2004; Spoerri et al., 2009). In particular SE stakeholders still use conventional materials for high-grade applications. Thus, a transition from an established trajectory of action (i.e. use of conventional materials) to an alternative trajectory of action (i.e. use of recycled materials) is required (Blum & Stutzriemer, 2007).

1.2.3 Ecological issues

A range of studies indicate that different applications of RMCM have lower, or at least comparable environmental impacts than conventional construction materials (Cassina, Plüss, Sutter, Angst, & Kronig, 2002; Hoffmann, Figi, & Leemann, 2006; Hugener, Deschwanden, & Bähler, 1999; Sani, Moriconi, Fava, & Corinaldesi, 2005; Tam, Gao, & Tam, 2006). However, environmental benefits of high-grade RC applications have been in doubt (Holcim, 2010). Since cement is the main contributor to many environmental impacts (e.g. Carbon Footprint) of concrete, additional cement use for RC due to the larger grain surface area of recycled aggregates (Cabral, Schalch, Carpena, & Duarte, 2010; Fonseca, de Brito, & Evangelista, 2011; Hoffmann & Jacobs, 2007; Limbachiya, Marrocchino, & Koulouris, 2007) might outweigh potential benefits of natural aggregate substitution (Weil et al., 2006). In addition, transport distances and types (Marinkovic, Radonjanin, Malesev, & Ignjatovic, 2010), and C&D waste composition and treatment (Mercante, Bovea, Ibáñez-Forés, & Arena, 2011) have been found to significantly affect the impact balance of RC. This implies that environmental benefits of different RC mixtures in comparison with conventional concrete (CC) are still uncertain. Furthermore, the sensitivity of such a comparison to additional cement for RC, C&D waste composition, and different transport distances is yet unclear.

1.3 A transition towards sustainable construction materials management

As outlined above, RMCM for high-grade applications might have the potential to mitigate the environmental impacts of the large and increasing amounts of C&D waste, but are currently not broadly accepted nor applied in Switzerland. Therefore, a transition towards a more sustainable construction materials management is required.

Generally, a transition can be defined as a gradual, continuous process of a system (e.g. firm, society) change where the structural character of the system transforms (Binder, 2005; Martens & Rotmans, 2005). It has been described as the phase of adaptation in which new socio-ecological and socio-technical regimes emerge and which lies in between two successive and more stable periods of development (Fischer-Kowalski & Haberl, 2007; Geels & Schot, 2007; Malaska, 1994; Rotmans & Loorbach, 2009).

Geels (2002) describes technological transitions as a change of the socio-technical regime, where the relation among the individual aspects of such regimes change (i.e. infrastructure, technologies, markets and user practices, sectorial policies, techno-specific knowledge, industrial networks, and cultural and symbolic meaning). Furthermore, these socio-technical regimes and their transformation are situated and influenced by broader landscape transformations and small-scale niche innovations, as described by the multi-level perspective (Geels, 2002, 2005). Landscape here refers to a broader, usually more slowly changing, external structure or context for interactions of actors in the regime. Niches, on the other hand are protected from normal market selection mechanism within the regimes and therefore allow for radical technical innovations as well as supporting social networks to emerge (Geels, 2002). Therefore, a successful transition can be described as the process where niche innovations flourish and slowly change the dominant socio-technical regime, potentially supported be exogenous structural factors, and eventually establish a new regime configuration.

Hence construction materials management systems can be described as socio-technical regimes. Key regime items would be mainstream materials applications (i.e. technologies), construction stakeholders' material preferences (i.e. user practices), norms and standards (i.e. sectorial policies), material research and experience (i.e. techno-specific knowledge), material supply and demand networks (i.e. industrial networks), image and trends (i.e. cultural and symbolic meaning), and structural and civil engineering stock (i.e. infrastructure). This conceptualisation immediately reveals that any transition in the construction sector is a multifaceted issue and that single-handed efforts (e.g. material niche innovations) might be doomed to fail. In addition and as outlined above, environmental benefits of recycled materials have been questioned. Although recycling is generally seen as favourable, a transition towards a system with more or closed loop recycling might not necessarily be more sustainable.

1.4 Understanding supply and demand, and related environmental impacts

In broad terms it can be said that sustainable construction materials management depends, (i) on an in-depth understanding of materials available (i.e. supply), and actors, their decisions and interaction affecting the demand; (ii) a robust analysis of the sustainability of alternative material options compared to conventional materials. These two research gaps are elaborated on below.

1.4.1 Supply and demand for RMCM

In order to assess the potential supply of future recycled materials it is essential to determine future waste streams under different scenarios. It has been shown that material stocks in use and their lifetime could be used as determinants to calculate resource demand and waste generation in the future (Baccini & Brunner, 2012). To determine future material flows it can be assumed that users are not primarily interested in the material flows but rather in the services they provide. Therefore services (e.g. usable floor are for SE) are suggested to be the main drivers of material stocks in use to and corresponding waste flows (Muller, 1998, 2006).

In Switzerland various studies have analysed current and potential future resource and waste flows in the construction sector on different scales (FOEN, 2001a, 2001b; Kohler et al., 1994; Kohler, Hassler, & Paschen, 1999; Lichtensteiger, 1998, 2006; Redle, 1999; Schneider & Rubli, 2007). Most of these focused on resource flows from and to SE (i.e. buildings, fewer studies focused on CE so far (Redle, 1999; Tanner, 2005)). However, although these studies generally demonstrate the great potential of reuse to mitigate C&D waste disposal, they rarely consider the demand side implications of such transition.

The slow adoption of, in particular, high-grade RMCM applications led to a shift of focus towards demand for RMCM (Moser et al., 2004; Spoerri, 2006; Spoerri et al., 2009; Uebersax, 2005) and to the question of: What triggers or hinders higher demand for RMCM? Frist of all, cost contemplations are brought up to be among the main factors affecting the demand of RMCM (Loughlin & Barlaz, 2006; Spoerri et al., 2009). However, with RMCM often priced in the same range as conventional materials (Robinson, Menzie, & Hyun, 2004) decision criteria other than price are likely to tip the balance in construction stakeholders' decisions. Consequently, a variety of criteria has been identified acting as barriers for a more widespread use of RMCM including; lack of information about technical properties and environmental impacts of RMCM, clear quality standards, governmental support and appropriately located recycling facilities, the "waste" image of RMCM and the availability of landfill as a cheap option for C&D waste treatment (Blum & Stutzriemer, 2007; Huang, Bird, & Heidrich, 2007; Moser et al., 2004; Poon, 2007; Rao et al., 2007; Robin & Poon, 2009; Spoerri et al., 2009). However, it is so far unknown how these criteria differ regarding different stakeholders, applications and material types involved, and how they quantitatively affect the individual decisions.

An additional factor, which may play an important role in changing stakeholders' behaviour towards more use of RMCM are the decision heuristics. Decision-making under uncertainty (Amihud & Lev, 1981; Finucane, Alhakami, Slovic, & Johnson, 2000) and adherence to the status quo (Pettigrew, 1973) may cause lock-in effects, preventing adoption of emerging technologies (Berkhout, 2002; Unruh, 2000; Witt, 1997). As individuals use decision heuristics to different degrees according to different roles (Busenitz & Barney, 1997), it is key to understand how construction stakeholders interact when deciding about RMCM.

Based on these observations the first research gap targeted by this research was identified.

Research gap 1: **Research is needed to jointly understand supply** (i.e. potentially available materials) **and demand for RMCM** (i.e. key actors, their decisions, and interaction among each other as well as with their socio-technical environment).

1.4.2 Sustainability assessment of construction materials

Sustainability is traditionally divided into the three pillars environmental, economic and social sustainability (World Commission on Environment and Development, 1987). Regarding mineral construction materials in Switzerland, social sustainability might be of minor concerns as mining and processing those seems to have minor direct health impact (Hugener, Emmenegger, & Mattrel, 2006), compared to for example metal mining activities. With material costs only representing a minor fraction of overall construction costs, and potential winners (i.e. recycling industry) and losers (i.e. natural aggregates mining) of a transition toward a closed-loop recycling system balancing out economic impacts, the economic sustainability of such transition is not heavily questioned either. However, concerns regarding the environmental sustainability of C&D waste reuse were raised (Holcim, 2010; Marinkovic et al., 2010; Weil et al., 2006).

Assessing the ecological sustainability is strongly linked with the life cycle assessment (LCA) approach standardized by ISO (ISO, 2006a, 2006b). Although there are other methods for environmental sustainability assessment such as environmentally extended input-output analysis (e.g. Lenzen, 1998; Nakamura & Kondo, 2002; Wiedmann, Minx, Barrett, &

Wackernagel, 2006), LCA is becoming the standard tool for environmental impact assessment on the product scale. In the construction sector, LCA is widely applied to assess and compare construction products, building parts, or systems (Weibel & Stritz, 1995). Additionally, comprehensive databases have been developed providing the life cycle inventories (LCI) for construction processes (Althaus, Dinkel, Stettler, & Werner, 2007; Kellenberger et al., 2007; Werner, Althaus, Künniger, Richter, & Jungbluth, 2007) and demolition processes (Doka, 2000, 2007).

Previous LCA of RMCM generally showed favourable results for the recycled materials compared to conventional materials. In particular recycled aggregates in CE showed clear benefits compared to natural aggregates due to the high on-site recycling rates (Carpenter, Gardner, Fopiano, Benson, & Edil, 2007; Chiu, Hsu, & Yang, 2008; Hugener, Mattrel, Schmid, & Fritz, 1998). This has only been questioned due to the release of polycyclic aromatic hydrocarbon in the recycling process of asphalt pavements with high bitumen contents (Hugener et al., 2006; Hugener et al., 1998), which consequently has been banned in Switzerland (VSS, 1998b). RMCM for SE application on the other hand, and in particular recycled concrete from mixed rubble (i.e. closed loop recycling) are questioned over their environmental benefits compared to conventional materials as already outlined above.

In addition, comparative LCA studies usually make assessments on the product level based on a functional unit, but how those results scale to the system level of a socio-technical transition is rarely considered. Depending on available supply (e.g. C&D waste) for alternative products and their speed of adoption (e.g. demand for RMCM) potential benefits have to be assessed from a systemic perspective.

From these limitations the second research gap considered in this research was derived.

Research gap 2: **Research is needed to understand environmental implications of a transition towards a more closed-loop construction material management.**

2 Objectives and research questions

The goal of this research was

to develop an agent-based model to simulate socio-technical transitions towards a more sustainable construction material management.

To address this goal and fill the research gaps mentioned above in the context of recycled mineral construction materials (RMCM) three main objectives were articulated.

The first objective was

to analyse supply and demand of RMCM.

This objective was articulated in two main research questions:

1. **What is the supply potential of RMCM from C&D waste?**

   This research question was answered through research published in **Publication III** of this thesis.

2. **How do actors decide and interact about the demand for RMCM?**

   Since a systematic approach to empirical operationalize agents for agent-based modelling (ABM) was lacking, the following sub question had to be addressed first:

   2.1. How can we empirically operationalize agents, their interaction, decision-making, and behaviour for context specific ABM?

   This research question was addressed in **Publication I** of this thesis, and provided the methodological procedure to address the second sub question:

   2.2. What are key actors, and how do they interact, decide and behave when demanding RMCM?

   This research question was addressed through the research published in **Publication II** of this thesis.

The second objective was

to develop an agent-based socio-technical model integrating supply and demand.

This objective was addressed by means of the third main research question:

3. **How can we enhance the demand for RMCM?**

   Based on the technical supply potential and empirical operationalised agents' decisions and interactions regarding the demand, both addressed under the first objective, answering this questing integrated supply and demand in an agent-based socio-technical model. This research question was answered through the research published in **Publication III** of this thesis.

The third objective was

to assess the environmental impacts of different simulation outcomes.

This objective was addressed through the fourth main research question:

4. **How can we align supply and demand with minimal environmental impacts?**

   This question relies on the understanding of the environmental impacts of recycled and conventional materials throughout their life cycle, which was addressed through the research published in **Publication IV** of this thesis. These results were then used to assess the outcome of the socio-technical model developed under the second objective.

3 Materials and methods

This section describes the methods and conceptual framework adopted to address the research goals and the case study of recycled mineral construction materials in Switzerland.

3.1 Methods and conceptual framework

3.1.1 Methodological procedure and conceptual framework

To address the different perspectives and aspects mentioned in the research questions above in a comprehensive way a conceptual framework was developed which outlines how the various methods were combined and integrated (Figure 1). The research was conducted in the following four modules.

Module 1: **Supply:** Material flow model of potential supply

Module 2: **Demand:** Empirical operationalization of actors' decisions and interaction

Module 3: **Supply & Demand:** Agent-based socio-technical model

Module 4: **Environmental impact assessment:** Life-cycle assessment (LCA)

Each one of these modules required a range of social, technical, economic and ecological scenario parameters, which were jointly developed to allow subsequent integration.

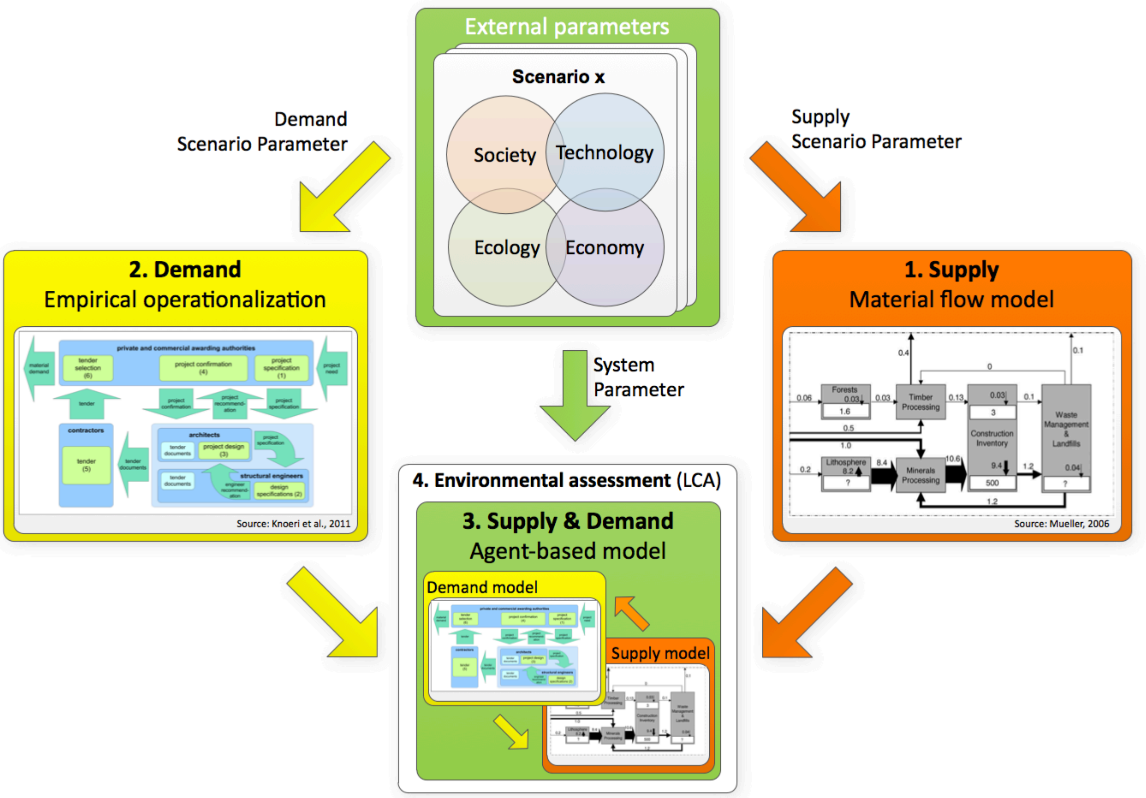

Figure 1: Conceptual framework

*3.1.2 Module 1: Material flow model of potential RMCM **supply***

Purpose: The purpose of module 1 was to analyse the supply potential of RMCM.

Methods: A streamlined material flow model was developed building on the outcome of previous studies (FOEN, 2008; Schneider & Rubli, 2007, 2009). In this streamlined model time series were derived from power law trend extrapolations of historical data from updated model calculations (i.e. SE C&D waste volumes) from Wuest & Partner AG published as Swiss Federal Office for the Environment report (FOEN, 2001a, 2001b, 2008). Annual potential supply [tons] of mixed and concrete rubble were derived from these fairly aggregated C&D waste data using C&D waste stream composition and densities (FOEN, 2008).

*3.1.3 Module 2: Empirical operationalization of actors' decisions and interaction regarding the **demand** for RMCM*

Purpose: The purpose of module 2 was twofold; first it aimed to develop a comprehensive approach to empirically operationalise actors' decisions and interaction for ABM, and second to analyse Swiss construction actors' decisions and interactions when demanding RMCM.

Methods: (i) The agent-operationalisation approach was developed based on a literature review of agent-based models for socio-ecological and socio-technical systems. This review focused on the three central issues limiting the exploitation of ABM's full potential; context specific application (i.e. beyond proof of concept), more behaviourally realistic agents rules, and validation of ABM. (ii) By applying the agent-operationalisation approach, Swiss construction stakeholders' decisions and interactions regarding RMCM were derived though expert interviews and workshops and quantified in a postal survey. The expert interviews were conducted in January 2007 and the expert workshops in May 2007 and January 2008. The survey was conducted between July 2008 and August 2009 sending out questionnaires to a random sample selected for each of the nine stakeholder groups.

*3.1.4 Module 3: Agent-based socio-technical model integrating **supply and demand***

Purpose: Module 3 aimed to analyse key factors enhancing the demand for RMCM in a transitions leading to a more closed-loop construction material system.

Methods: An agent-based model of the Swiss recycled construction material market based on empirical data derived from the agent operationalization approach was developed, demonstrating how detailed empirical agent decision data could incrementally be included. Key factors affecting the demand for RMCM were derived from sensitivity analysis. Intervention scenarios to steer the system towards sustainable construction waste management were developed and assessed. With ABM being the core method of this research the choice of ABM is briefly elaborated on below.

3.1.5 *Module 4: Life-cycle* ***environmental impact assessment***

Purpose: The aim of Module 4 was to assess the environmental impacts of RMCM compared to their conventional alternatives, and to use these results to evaluate the outcomes from the socio-technical model developed in Module 3.

Methods: A standard comparative LCA of conventional concrete (CC) and recycled concrete (RC) was established. Allocation is avoided by system expansion and substitution according to ISO 14044 (ISO, 2006a). A functional unit of 1 m3 of concrete of a specific strength class at the construction site was selected. The life cycle impacts of 12 recycled concrete (RC) mixtures with two different cement types were analysed and compared with the impacts of corresponding conventional concretes (CC) for three SE applications. The results of this comparison were then combined with the outcome of the socio-technical model.

3.2 Introduction into Agent-Based Modelling (ABM)

With ABM being the core method of this research, the following chapter provides an introduction into ABM and elaborates on the choice of ABM for addressing socio-technical transitions towards sustainable construction material management. Firstly, a brief overview over the history of social simulation in general and ABM in particular is provided. Secondly, the basic characteristics of ABM are introduced. Thirdly, the use of ABM for the simulation of socio-technical transitions is elaborated on, and the choice for the Swiss construction material case is motivated.

3.2.1 History of social simulation

Generally social science simulation goes back to 18th century starting with differential equations, which are the basis for the current system dynamics simulation. ABM in contrast is a relatively "young" tool and can be traced back to the 1940ies. One of the basic ideas behind ABM relates to the self-reproduction machine postulated by John von Neumann in 1948. Holistic system properties are generated from single modules whereas the behaviour of the modules is only determined by simple rules and not by the whole context. In the late Sixties John Convey first did the shift from this theoretical idea to a practical implementation. With the "Game of Life" he programmed the first cellular automata in which complex patterns emerge from simple rules (Gardner, 1971). A next milestone was laid by Schelling (Schelling, 1978) when he built a model to show how urban segregation could emerge through unplanned interaction on the micro-level. He was able to show that, even with a very high level of acceptance of other ethnics in the neighbourhood, segregation occurs. Together with the model of flocking birds from Craig Reynolds presented in 1986, Schelling's segregation model showed the great potential of ABM for the simulation of socio-ecological systems for the first time (Reynolds, 1987).

ABM and many other computer-aided applications would not have developed so far without the efforts in artificial intelligence and artificial life. The term "artificial life" became generally known after a workshop organised by Christopher G. Langton in 1987 with the same name. In Langton's workshop, scientists from different research fields concluded that many phenomena of living systems could not be modelled linearly. Based on these conclusions, Langton stated a paradigm change in modelling of living systems:

".......bottom-up rather than top-down modelling, local rather than global control, simple rather than complex specifications, emergent rather than pre-specified behaviour and population rather than individual simulation (Langton, 1987)."

A further major contribution in the field was the book "Growing Artificial Societies" from Epstein and Axtell (1996). In the "Sugarscape" model they retrace fundamental collective behaviours such as group formation, cultural transmission, combat, and trade emerge from the interaction of individual agents following a few simple rules. They view artificial societies as:

"…..laboratories, where we attempt to 'grow' certain social structures in the computer – or in silico – the aim being to discover fundamental local or micro mechanisms that are sufficient to generate the macroscopic social structures and collective behaviours of interest."

3.2.2 Characteristics of ABM

Gilbert (2008) formally describes ABM[1] as "*a computational method that enables a researcher to create, analyse, and experiment with models composed of agents that interact within an environment*". A similar view is taken by Janssen (2002) describing ABM as "*consisting of a number of interacting autonomous agents*". Based on interdisciplinary complexity science (Axelrod, 1997b; Holland, 1995), Grimm and Railsback (2005) describe one key characteristics of ABM as: *"Systems are understood and modelled as collections of unique individuals. System properties and dynamics arise from the interaction of individuals with their environment and with each other."*

Common among the above-mentioned ABM definitions and many others (e.g. Cedermann, 2005; Epstein & Axtell, 1996; Gilbert & Troitzsch, 2005; Tesfatsion, 2002) are the three key ABM components – agents, their behaviour and environment – and the emergence of system properties from the interaction of autonomous, heterogeneous agents. These three key components are addressed in turn below:

Agents: In social simulations, agents usually represent parts of the social world (e.g. individuals, groups, organisations, institutions or societies); They could also represent natural (e.g. cells, organs, plants, animals, populations or ecosystems) or physical entities (e.g. atoms, molecules, machines, production lines, manufactory plants or industries). Most ABM applications deal with numerous and heterogeneous agents (Axelrod, 1997b; Epstein & Axtell, 1996). But what defines an agent or the concept of agency? Applied to people, agency is related to concepts such as intentionality, free will, and the power to achieve one's goal (Gilbert & Troitzsch, 2005). However, as this is difficult to operationalize for computer agents, Wooldridge and Jennings describe computer agents as software entities that are autonomous, reactive, pro-active and capable of social interaction (Jennings, 2000; Wooldridge & Jennings, 1995). Consequently, one could say that agents are mostly defined though their behaviours.

Agents' behaviour: The types of behaviours implemented in ABM vary from very simple if-then rules to highly complex optimisation or learning algorithms. However, according to Parker et al. (2003) agents' behaviour can generally be described as follows: It is mainly defined through the local interaction with other agents and the environment and basically independent from central control. The local interaction itself describes the interaction of agents among their direct neighbour agents and their local environment. Interactive agents allow for the simulation of

[1] There are numerous terms for Agent-Based Models or Modelling (ABM) (e.g. Multi-Agent Simulations (MAS), Individual-Based Models or Simulations, Agent-based Simulations). In this research we use ABM as a general synonym including the above-mentioned terms.

adaptive or learning behaviour. Agents do not necessarily have to react in a fixed network or structure; they also can change their networks and/or hierarchical structures.

Environment: The agents' environment is the virtual world in which agents act (Gilbert, 2008). What exactly the environment represents and how complex or simple it is implemented, depends on the task at hand. The environment might take the form of grid, representing the explicit geographical spaces or other features such as knowledge space. An other option is a link based environment where no special representation is implemented and agents are only connected through a network of links (Gilbert & Troitzsch, 2005).

Modelling and simulation: Besides, agents, their behaviour and environment, simulation or the experimental use of computational models is another common ground among ABM definitions. According to the general modelling theory (Stachowiak, 1973) a model can be defined as "a purposeful simplified representation of the reality". Or more formally, according to Minsky (1968), "*To an observer B, an object A* is a model of an object A to the extent that B can use A* to answer questions that interest him about A."*

Modelling and simulation is not a linear process and the model is usually not the main output but rather the problem we solved with it, or the research question we answer. Any model building process should therefore start with the purpose or problem entity. The modelling process itself is often described as an iterative procedure or "modelling cycle" (Gilbert & Troitzsch, 2005; Grimm & Railsback, 2005; Page, 1991; Sargent, 1982). Based on data and knowledge about the problem entity (i) a conceptual model (ii) is designed, and implemented into a computer model (iii). In an experimental setup several simulation runs with the computer model lead to simulation results (iv), which then can be compared with the problem entity and interpreted. These four phases of model design, implementation, experimentation, and interpretation are iteratively repeated until the question is sufficiently accurate answered.

The question is then, when is my model sufficiently accurate for the problem at hand? The first answer could be, when the model output matches my real system. Such operational validation is still the gold standard in model validation, but with increasingly complex computer models, validation of the conceptual models (e.g. through participatory modelling), verification of the code (e.g. reproduction of models), and validation of the experimental design gain importance. However, validation may have different meanings for different model purposes (Küppers & Lenhard, 2005) which is why different validation techniques and procedures exist (Louie & Carley, 2008; Moss, 2008).

3.2.3 ABM of socio-technical transitions

ABM is increasingly becoming a standard tool for analysing and modelling transitions in complex socio-ecological (Grimm & Railsback, 2005; Janssen & Ostrom, 2005) and socio-technical systems (Bergman et al., 2008; Chappin & Dijkema, 2010; Haxeltine et al., 2008; Schwarz & Ernst, 2009). This is due to ABMs` ability to capture the effects of the interactions between heterogeneous individuals and networks on the system (Garcia, 2005; Rahmandad & Sterman, 2008). The mineral construction materials market in Switzerland shows exactly these attributes, as local interaction and adaptation determines demand for RMCM.

Most of the previous ABM studies analysing socio-technical system transitions are energy focussed. They study either consumer goods such as lighting (Axtell, Andrews, & Small, 2001), or household energy generation and transformation such as photovoltaic systems (Ramanath & Gilbert, 2004), domestic micro-cogeneration (Polhill, Parker, Brown, & Grimm, 2008), heating systems (Svenson, 1990), bio-electricity (Davis, Nikolic, & Dijkema, 2010), and occupancy behaviour (Andrews, Yi, Krogmann, Senick, & Wener, 2011). Just recently, ABM has started to be used to explicitly address sustainable material flow management, (e.g. Bollinger at al. (2011)) and showed its potential to enhance understanding of drivers behind material flows and recycling schemes. Thus, ABM not only meets the specific requirements of the case study but its application also presents a new example of sustainable material management and contributes to a growing field of socio-technical transition simulation studies (Bergman et al., 2008; Haxeltine et al., 2008; van Dam, Nikolic, & Lukszo, 2013).

3.3 Case study: RMCM in Switzerland

3.3.1 System boundary and construction sectors

Although recent statistics show an increasing amount of mineral construction materials (especially gravel) being imported, in general mineral construction materials markets are local or regional due to the high specific weight of the products and the consequently high transport costs (Binswanger & Siegenthaler, 1995; Eberhard, 2014; HASTAG, 2014; Redle, 1999). Therefore, the system boundary for this research was set to the Swiss border.

With RMCM already fairly established and accepted in CE, where they are applied in more than 30% of all cases, this research mainly concentrated on RMCM application in SE. This can be justified by the low acceptance of RMCM in SE on one hand (e.g. Spoerri et al., 2009), and by the much debated environmental benefits of SE RMCM application on the other hand (Holcim, 2010). However, construction stakeholders' decisions and interaction were still analysed in both sectors to allow for comparable insights.

3.3.2 Materials applications considered

Construction sectors in general are highly regulated and this is also true for Switzerland. With norms regulating the application of RMCM dating as far back as 1994 (SIA, 1994), today the reuse of C&D waste is extensively regulated in Switzerland. Specification of C&D waste types and recycled aggregates (i.e. intermediate products) are mainly set by the federal office for the environment (FOEN, 2006). Their application in CE is normalized by the Swiss association of roads construction experts (VSS, 1998a, 1998b, 1998c, 1998d, 1998e), and concrete application in SE by the Swiss Association of Engineers and Architects (SIA, 2010).

Figure 2 shows the recycling routes for different C&D waste types and the conventional alternatives. For the purpose of this research three applications from CE (i.e. bonded, and unbonded sub base layers and lean concrete), and three applications from SE (i.e. outdoor concrete, indoor concrete and lean concrete applications) have been selected. The only application excluded was asphalt layers where asphalt pavement debris could be reused. However, due to the issue with polycyclic aromatic hydrocarbon this recycling route is highly regulated and controlled. In addition, the potential volume of expected waste to be reused through this route is negligible in comparison.

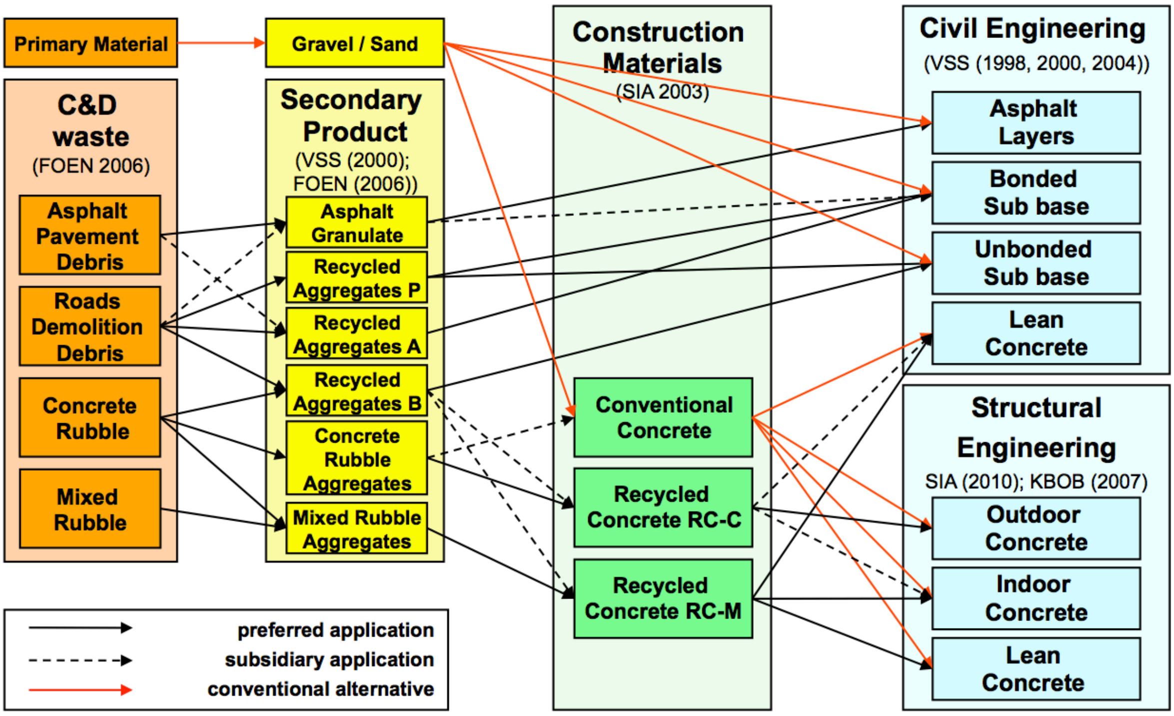

Figure 2: Recycling routes for different C&D waste types into RMCM and their conventional alternatives (solid arrows: preferred application, dotted arrows: subsidiary application, red arrows: conventional alternatives), **based on Swiss norms, standards and recommendations.**

4 Results

4.1 Potential RMCM supply from C&D waste

RMCM have a significant supply potential in Switzerland. Our model shows, that the expected waste streams could provide up to 40% of the required aggregates for new SE[2] construction (Knoeri, Nikolic, Althaus, & Binder, 2014). The potential mixed rubble supply is almost three times the volume and double the weight of the potential concrete rubble supply, approximately reflecting the C&D waste composition in SE (FOEN, 2008).

Comparing the potential supply of RMCM with different demand scenarios allows for a first analysis of the demand implications of a closed-loop construction material management. With the current demand (~11%) only a fractional amount of the mixed and concrete rubble supply is reused. Considering the potential material flows only, closed-loop management, where the expected rubble flows are fully reused within structural engineering, seems to be possible. This however, would require recycled concrete (RC) to become the standard for all structural engineering applications (100%), substitute 40% of the aggregates, and use mixed rubble aggregates (RC-M) for 70% of all applications.

Further, the relatively small amount of potential lean concrete applications shows that only a tiny fraction of C&D waste could be reused as lean concrete. Considering the generally decreasing demand from civil engineering, and the reservation of civil engineering actors against RMCM from structural engineering, RC for structural applications seems to be the only solution for the reuse of C&D waste from SE.

However, future C&D waste volumes strongly depend on construction investment scenarios and related stock dynamics. While in a trend scenario construction waste volumes seem to level off, they might increase by 50% or decrease by 25% in 2050 compared to 2008 levels. Therefore depending on future construction activity the C&D waste problem might be drastically exacerbated or slightly alleviated.

Key results:

- RMCM have a large supply potential (- 40% of required aggregates in SE)
- Mixed rubble potential three times higher than for concrete rubble
- Closed-loop management within structural engineering possible
- Requires recycled concrete as a standard, 40% substitution, and 70% RC-M

Contribution to the topic: As a prerequisite step this analysis provided in-depth understanding of the RMCM system and the technical supply background system for the subsequent demand and supply model development.

[2] As mentioned under 3.2 the modelling part of this thesis concentrated on structural engineering (SE)

4.2 Actors' decisions and interaction about the demand for RMCM

4.2.1 Empirical agent operationalization

During the last decade, agent-based modelling (ABM) has demonstrated its potential in various research fields (Axelrod, 1997b; Epstein & Axtell, 1996; Gilbert & Troitzsch, 2005; Janssen, 2002; Tesfatsion & Judd, 2006), but not without contradictory trends. The three central questions being raised are: (i) How to go beyond a "proof of concept" (e.g. Janssen & Ostrom, 2006; Matthews, Gilbert, Roach, Polhill, & Gotts, 2007) (ii) How realistic are agents with simple behavioural rules? (e.g. Jager & Janssen, 2002; Mosler & Tobias, 2005) (iii) How could or should agent-based models be validated? (e.g. Axelrod, 1997a; Louie & Carley, 2008; Windrum, Fagiolo, & Moneta, 2007). The agent operationalization approach was developed to jointly address these three challenges (Knoeri, Binder, & Althaus, 2011a).

The approach is based on the conceptual framework for modelling socio-ecological as well as socio-technical systems with ABM presented in Figure 3. The theoretical foundations of the approach are Giddens' structuration theory (Giddens, 1984), the theory of planned behaviour (Ajzen, 1991), and structural agent analysis (Binder, 2007). The framework captures the three key elements of ABM; (i) agents (decision-making and behaviour), (ii) social structures (rules and resources), and (iii) the agents' environment. It includes the consequences of the agents' behaviour on social structures, environment and other agents' decisions, as well as the impact of past behaviours, other agents, social structure, and perceived environmental consequences on agents' decision-making.

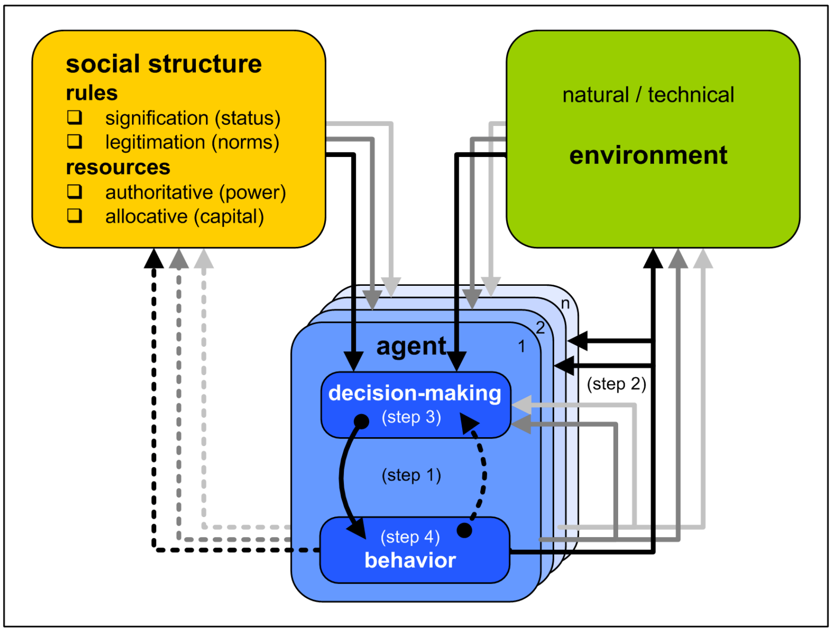

Figure 3: Conceptual framework of the interaction between social structure, agents and the environment (continuous arrows indicate synchronic, dotted arrows indicate diachronic impacts) (Source: Knoeri et al. (2011a), adapted from Binder (2007), Giddens (1984) and Nikolic (2009))

Empirically operationalizing key agents, their interaction, decision-making, and behaviour is crucial for agent-based modelling, as systemic behaviour emerges from local agents' behaviours and interactions (Axelrod, 1997b; Gilbert & Troitzsch, 2005; Janssen, 2002; Tesfatsion & Judd, 2006). The agent operationalization approach provides a stepwise procedure to do exactly this. Each step has a sound theoretical background and data collection method tailored to the specific problem addressed, which precise definition is a prerequisite.

In the Swiss construction material case, based on social network theory (Wasserman & Faust, 1994) and cross-impact analysis (e.g. Scholz & Tietje, 2002; Vester, 2007), key system actors were identified using an actor impact analysis (step 1). The interaction of those actors was determined in expert interviews and an expert workshop (step 2). The quantification of their decision-making was based on analytical hierarchy process (AHP) (Saaty, 1990), and done through survey methods (step 3). Finally, behavioural consistency analysis and conceptual validation (step 4) was performed using the survey results.

Applying the approach to the case study demonstrated its' practicality and provided a transparent and well-founded methodological procedure for data collection and integration in the subsequent model development phase. Within the limits of the constituent theory the approach is applicable to a broad field of socio-ecological and socio-technical system modelling problems with ABM.

Contribution to the topic: The agent operationalization approach provided a comprehensive framework to empirically operationalize key system agents, their interaction, decision-making and behaviour regarding the demand for RMCM.

Contribution to ABM: The approach addresses three major shortcomings limiting a full exploitation of ABM's potential; (i) "proof of concept" applications that are too theoretical, (ii) agents that are too simple, not behaviourally realistic, and often lack an empirical basis, and (iii) too much value is placed on operational instead of conceptual

4.2.2 Key actors' interaction, decisions & behaviour regarding the demand for RMCM

Awarding authorities, engineers, architects, and contractors were identified as key construction stakeholders regarding the demand for RMCM (Knoeri et al., 2011a). Selecting the key connected actors to be included in ABM ensures that system actors that are most affected and have the most impact will be included in the model which is consistent with social network theory (Faust, 1997; Wasserman & Faust, 1994). Nevertheless, other actor groups, especially active actors having much impact on the system, may be considered in addition for being operationalized as agents in ABM. Since regulation authorities were only weakly influenced by the system, they were included as external parameters in the RMCM case study, which allows simulating the effect of different regulation practices.

Awarding authorities interact with engineers, architects and contractors throughout the life stages of a construction project (i.e. initial specification, design, confirmation, tender selection, and construction) through specific decision-making processes in the Swiss RMCM case study (Knoeri et al., 2011a). However such an interaction chain is highly context dependent (e.g. local construction market and standards), and therefore, not generalizable to nearby or associated decisions. For example energy efficiency renovations might include a broader range of stakeholders (e.g. energy performance advisors or heating system engineers) or different interaction pattern. Each of those interactions requires to a certain extent a selection decision determining with whom to work. According to literature (Ling, 2002) key selection criteria in the building sector are job experience, reputation and personal contact, and economic considerations, where personal contact was most important in the Swiss RMCM case study (Knoeri, Binder, & Althaus, 2011b).

Throughout the interaction chain the interaction criterion (i.e. recommendation or specification from previous stakeholder) was the most important criterion in each material specific decision with the exception of the structural engineers' design specification, which was mainly determined by law, standards and experience. By contrast, the awarding authorities' initial project specification for sustainable construction had little weight in structural engineers' decisions. Besides that, and somehow in contrast to the widespread opinion that the cheapest technical feasible option will be applied (Uebersax, 2005), economic aspects were not the most important criteria when deciding about RMCM (Knoeri et al., 2011b).

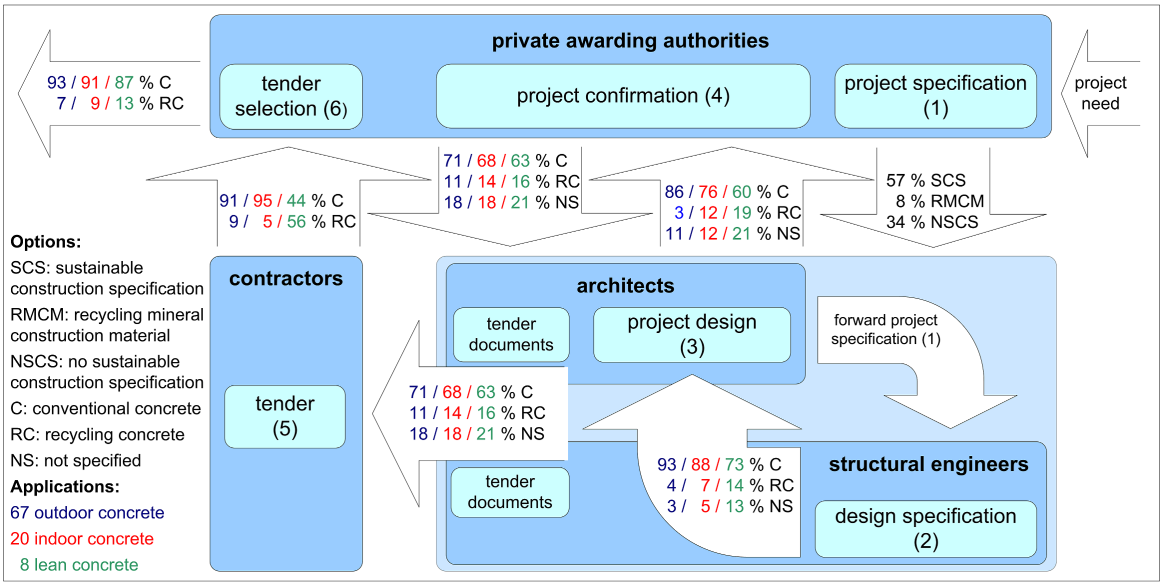

Figure 4: Behavioural frequencies in structural engineering (The applications are indicated in colour for material specific decisions (e.g. 2-6), source: Knoeri et al. (2011b)).

Figure 4 shows the behavioural frequencies of construction stakeholders in structural engineering (Knoeri et al., 2011b). The first key result is the contrast between the high preference for sustainable construction of awarding authorities in their project specification (1) with the low specification and recommendation frequencies in the decisions thereafter. This indicates that construction experts do not yet link sustainable construction with RMCM. The second point is the lack of differentiation between different applications in structural engineering. Besides the much higher acceptance of RMCM in civil engineering (CE), this is one of the key sectorial differences and demonstrates higher RMCM knowledge penetration in CE confirming findings from previous studies (Moser et al., 2004; Spoerri et al., 2009).

We found that stakeholders make their decisions mostly rationally. This was shown by reasonably consistent judgments in the AHP procedure meaning, that most stakeholders take carefully reasoned decisions where they seek a cognisant balance among given alternatives regarding different criteria (Svenson, 1979, 1996). However, construction experts more frequently involved in construction decisions had slightly less consistent AHP judgement, indicating that they might use simpler decision heuristics (Johnson, Payne, & Bettman, 1988; Jungermann, Pfister, & Fischer, 1998). Further, stakeholders behaved rationally by choosing the highest ranked alternative in 75% of all cases when making decisions, even if their AHP judgements were slightly less consistent. Thus, quantifying decision-making with AHP provided a good model for mirroring behaviour.

Key results:

- Awarding authorities, engineers, architects, and contractors identified key actors
- Interaction criterion most important but sustainability specification with little impact
- Crucial role of engineers, which decide mainly based on experience and standards
- Preferences for RMCM decrease throughout the process
- RMCM broadly accepted in CE but niche product in SE
- Mostly rational decision-making and behaviour

Contribution to the topic: This analysis helped to understand construction stakeholders' reluctance to a broader use of RMCM and sectorial differences.

Contribution to ABM: This research provided empirically based and tested agent decisions rules and data for the subsequent agent based model.

4.3 Simulating demand in an agent-based supply & demand model

Construction stakeholders' awareness of RMCM as an option in the decision process was one of the key factors to enhance the application of RMCM. This included considering sustainable construction in general in the initial project specification decision by awarding authorities as well as construction actors being aware of RC as an option in subsequent material decisions. Awarding authorities already considered sustainable construction in about 50% of cases at the beginning of the construction project. Therefore, raising their awareness to 100% increased the overall fraction of applied RMCM only by about 5%. This is due to the weak association of sustainable construction in general with RMCM by architects and engineers. This implies that an improvement of such linkage will trigger its demand (Figure 5). Further, the demand showed price elasticity in a particular range (about 20%) around current prices, while larger differences had little additional effect (Knoeri, Nikolic, et al., 2014).

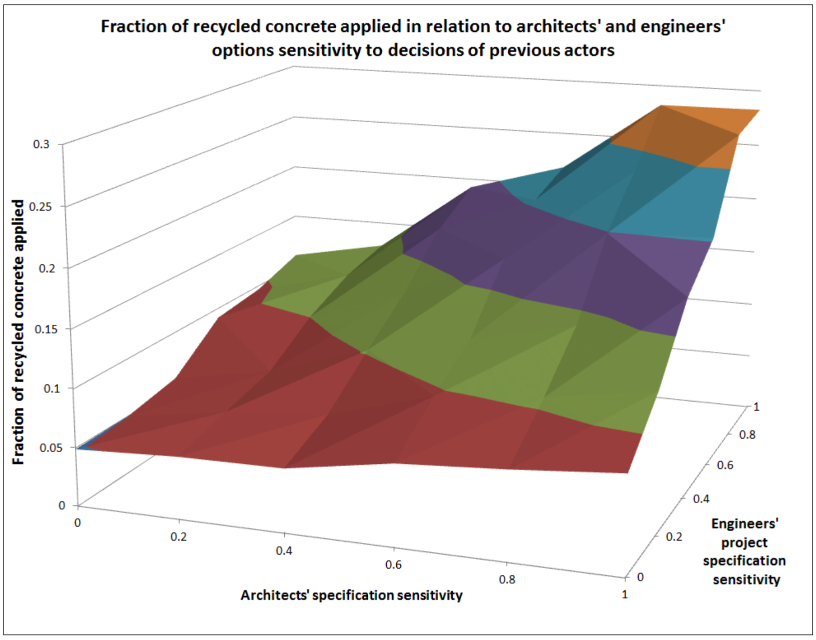

Figure 5: Recycled concrete fractions' sensitivity to changes in architects` and engineers` sensitivity to the project specification (0 if they consider options independent from awarding authorities` project specification, 1 if sustainable construction is specified they always consider recycled concrete as an option, displayed are mean values from 20 runs per parameter setting. Source: Knoeri, Nikolic, et al. (2014))

Based on the demand sensitivities and potential levers for policy interventions three distinct (i.e. information, public initiative, and economic incentives) and two combined scenarios were developed. The information scenario aimed at raising construction stakeholders' awareness of RMCM but in particular engineers' and architects' association of sustainable construction with RMCM. The public initiative scenario simulated the effect of isolated public efforts through their own projects and improving norms regarding RMCM. Economic incentives included a 10% price advantage for RMCM.

The most effective interventions for a transition towards a closed-loop recycling were extensive information combined with small economic incentives leading to 70% demand for RC of all demand for concrete (Knoeri, Nikolic, et al., 2014). The campaigns should address in particular architects and engineers and inform about the option of recycled materials. However, complete reuse in particular of the large amounts of mixed rubble might require higher aggregates substitution rates as the current 40%, or further making RC to the mainstream type of concrete applied (Figure 6).

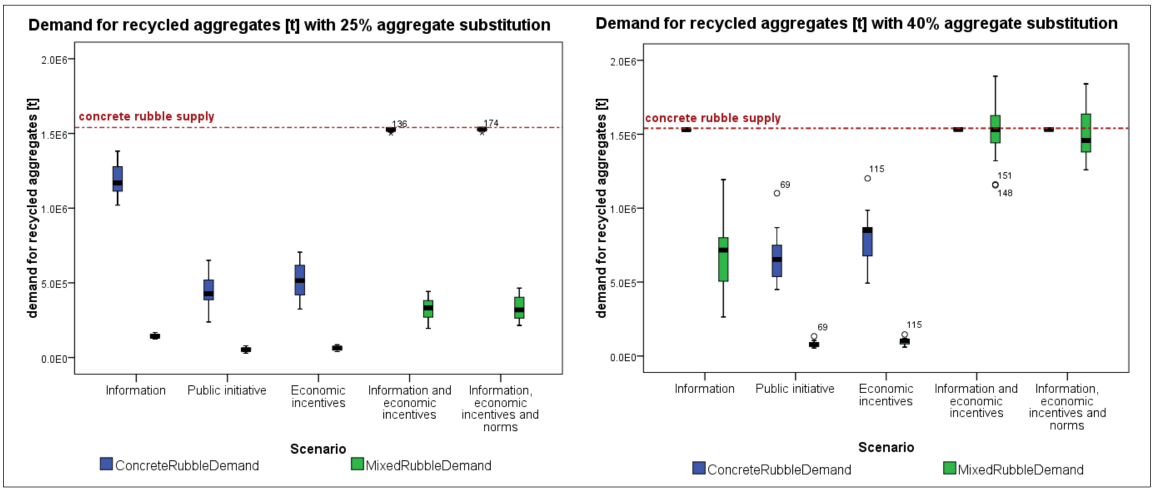

Figure 6: Annual demand for recycled aggregates (i.e. concrete rubble (blue boxes) and mixed rubble (green boxed)) **in different scenarios in comparison to the potential concrete rubble supply for two different aggregate substitution fractions,** (left 25%, right 40%) (Source: Knoeri, Nikolic, et al. (2014)).

Having extensive empirical data about agents` decision-making processes, and behaviour at hand, raised the question of the level of detail of this data that should be implemented in the model. Following the model development cycle (e.g. Grimm & Railsback (2005), and Sargent (2008)) we iteratively added or changed the decision traits in the model until a sufficiently accurate representation of the about 11% demand for recycling materials reported (FOEN, 2001a, 2008; Moser et al., 2004) was reached.

This analysis exemplifies, using the data from the agent operationalization approach, how environmental innovations in complex socio-technical systems could be captured with empirically based ABM. It demonstrates the value of empirically operationalized agent architectures on one hand, but emphasises the importance of an iterative model development on the other hand. This is highlighted by the fact that option awareness, one of most important factor for a realistic demand representation, was not operationalized beforehand but discovered through iterative model development.

Key results:

- Demand for RMCM most sensitive to construction stakeholders` awareness of this option and architects' and engineers' reaction to previous decisions
- Information campaigns with small price incentives most effective to boost demand
- Closed-loop recycling for all concrete rubble and for about $^{1}/_{2}$ mixed rubble possible
- Realistic demand when option awareness and multi-criteria decisions were included

Contribution to the topic: The sensitivity analysis highlighted the importance of knowing RMCM as an option in the decision process. The results showed that alignment of supply and demand is possible with reasonable intervention scenarios, but a completely closed-loop would require RC to become the standard.

Contribution to ABM: This research exemplified the application of the agent operationalization approach developed, but highlighted the importance of an iterative model development despite solid empirical agent data. Further, the context specific agent based model showed the potential of using ABM to address "real world problems" and therefore going beyond proof of concept studies.

4.4 Environmental impacts assessment

The aim was to establish a comparative LCA of conventional concrete (CC) and recycled concrete (RC) and to analyse the effect of cement content and transport distances. The system includes all processes from aggregates' extraction (CC) and building dismantling (RC) to ready-for-use concrete on the construction site. The functional unit is 1m^3 of concrete of a specific strength class at the construction site (Figure 7) (Knoeri, Sanyé-Mengual, & Althaus, 2013).

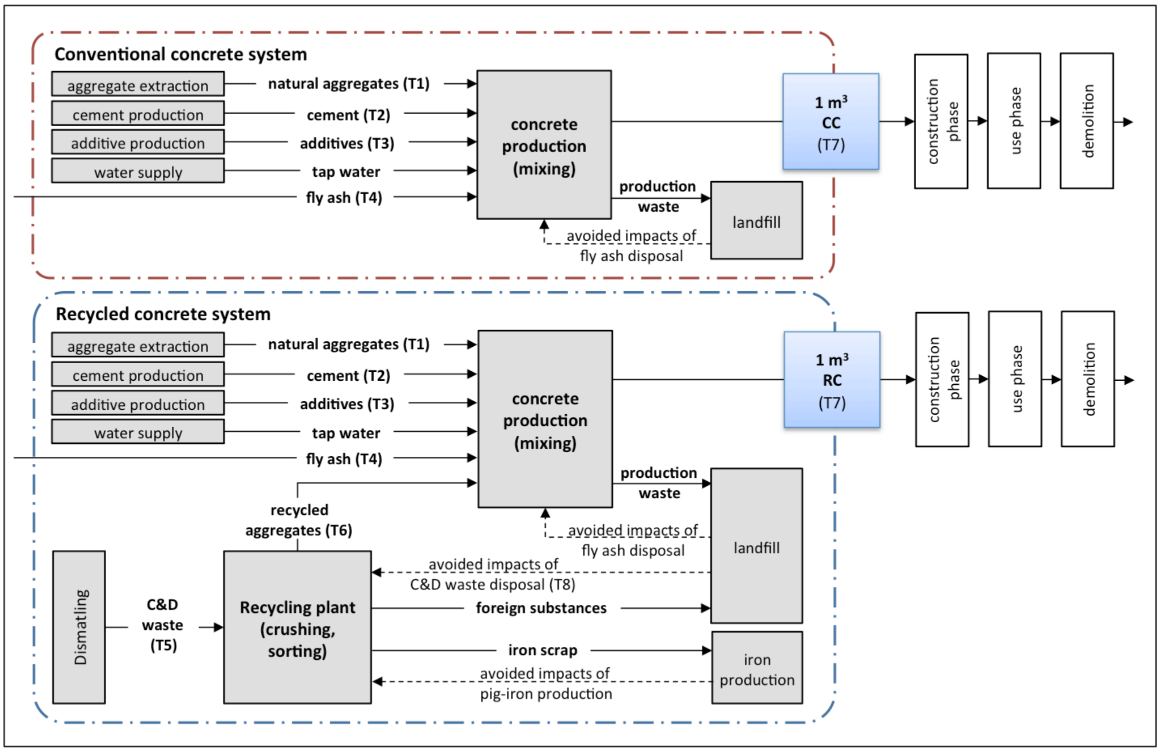

Figure 7: System boundaries, processes and materials for the conventional concrete and the recycling concrete systems (Light blue box indicates reference products, grey boxes processes, solid arrows product flows and dotted arrow avoided impacts considered. Source: Knoeri et al. (2013))

RC mixtures for structural concrete applications have significant environmental benefits compared to CC with the same cement type (mean 31%, StD 9%) at endpoint level. However, they have similar global warming potential (GWP) due to higher cement content when recycled aggregates are used (mean reduction for RC 5%, StD 7%). Corresponding to previous studies (Marinkovic et al. (2010); Holcim (2010); Weil et al. (2006)) cement and transport were identified as the main contributor to environmental impacts of concrete. However the difference between RC and CC impacts is mainly due to the avoided impacts from C&D waste transport and landfilling and those of pig-iron production (i.e. due to iron scrap recovery). This confirms that the unfavourable results for RC in previous studies are due to the exclusion of benefits from co-products of the recycling process.

The additional amount of cement needed for RC is key for its environmental performance. The impact comparison with the rather unfavourable GWP shows that limiting the additional cement to about 10% compared to the amount used in CC keeps the impacts comparable to CC.

For the Swiss reference transport distances all RC mixtures have lower environmental impacts than CC for all indicators. However, additional transport for RC above 15 km starts to shift the balance again for GWP. We can conclude that C&D waste reuse in high-grade structural concrete applications has not only the potential to conserve natural gravel resources and limit waste streams to landfills but also to mitigate wider environmental impacts.

Key results:

- Clear (≈30%) environmental benefits of RC compared to CC
- Difference mainly from avoided pig-iron production and C&D waste disposal
- Limit additional amount of cement (≈10%) and transport distances (≈15km) for RC

Contribution to the topic: The results support the action already taken to enhance the use of RC in Switzerland through norms and standards (Minergie, 2014; SIA, 2010). In addition, clear thresholds for a sustainable use of RC are provided.

Contribution to LCA: This research addresses previous doubts about the environmental benefits of RC compared to conventional concrete. Cement production is still the main contributor, but considering benefits from recovered steel scrap and avoided impacts of C&D waste disposal, shifts the balance in favour of RC.

4.5 Synthesis: Aligning supply and demand with minimal environmental impacts

Information scenarios combined with small economic incentives might increase the demand for RC up to 70% of all concrete applications. With an environmental benefit of 30% per m^3 of concrete applied compared to conventional concrete this would lead to a total environmental impact reduction from the concrete production in Switzerland of approximately 20%.

A complete reuse will require a shift towards recycled concrete as a standard or higher aggregate substitution rates. This might lead to unintended consequences though, such as increasing environmental impacts due to larger transport distances and higher cement demand required to produce recycled concrete of the same quality as conventional concrete with increased aggregate substitution. As shown above differences in transport distances larger than 15km or additional cement contents above 30kg per m^3 lead to higher environmental impacts than comparable conventional concrete. However, to break even with the current system regarding overall environmental impacts, the remaining 30% of RC applications would need significantly (i.e. more than double) higher environmental impacts than conventional concrete. As this is highly unlikely even a closed-loop recycling system would be environmentally beneficial compared to the current system dominated by conventional concrete.

Synthesising the results of the ABM and the LCA allows for the deriving of a new quality of results. First, an assessment of the environmental reduction over a whole system (i.e. about 20%) under different scenarios is possible. Second, implication of potential extreme scenarios (e.g. complete reuse with higher aggregate substitution rates) could be put in context and their environmental impacts assessed from a systemic perspective.

Key results:

- Enhanced demand for RC could reduce total environmental impacts by about 20%
- Complete reuse might occasionally push the limits of sustainable RC application
- But from a system perspective even complete reuse looks more sustainable

Contribution to the topic: The scale of reduction shows that there are significant environmental gains to make when shifting towards higher use of RMCM, but pushing towards a complete reuse might have some adverse effects.

Contribution to ABM and LCA: Integrating ABM and LCA results allowed a systemic assessment of different construction management scenarios. The link of an explicitly modelled foreground system (ABM) with a standard attributive LCA makes a step toward a more dynamic and consequential assessment of environmental impact related changes in socio-technical systems

5 Discussion

This research contributed to the method of agent-based modelling by developing the agent operationalization approach to empirically operationalize agents' decision and interaction, demonstrating an ABM example for socio-technical transition management, and integrating ABM and LCA for a systemic environmental impact assessment. Contributing to the case study, this thesis revealed construction stakeholders' preferences and decision-mechanisms, developed policy recommendation to enhance the demand for RMCM, and provided guidelines for a sustainable application of RMCM.

These contributions are elaborated on in two parts: First, the relevance of the findings is discussed from a methodological and case study point of view. Second, open issues and further research for ABM, socio-technical transition research, LCA, and construction material management are highlighted.

5.1 Relevance

5.1.1 Method: Agent-based modelling

To the field of ABM this research made three distinct contributions; The first, with:

the development & exemplification of the agent operationalisation approach.

The agent operationalisation approach provides a comprehensive framework to operationalize key system agents, their interaction, decision-making and behaviour for ABM. It therefore addresses three major concerns limiting ABMs' full potential: (i) Going beyond a "proof of concept" (e.g. Janssen & Ostrom, 2006; Matthews et al., 2007): The approach gives a specific strategy for embedding empirical knowledge into modelling practices. The credibility of models is enhanced through a step-by-step participatory approach for identifying relevant agents and analysing their interaction chain. (ii) Behaviourally realistic agents (e.g. Jager & Janssen, 2002; Mosler & Tobias, 2005): The model's parameters space to scan is reduced by providing an array of sample agents with empirically quantified decision-making and behaviour. (iii) Conceptual validity (e.g. Axelrod, 1997a; Louie & Carley, 2008; Windrum et al., 2007): The approach enhances the conceptual model validity by providing a way to empirically test one's theoretical assumptions.

The exemplification of the approach by means of the Swiss mineral construction material case study demonstrated its practicability. However, having a vast amount of empirical agent data ready available early in the model development might tempt a premature implementation of overly complex models. Therefore, this research highlights or in fact, reiterates (Grimm & Railsback, 2005; Sargent, 2008) the importance of an iterative model development. This allows for tracking the effect of each additional feature on the results and therefore avoiding the pitfall of overly complex models with blurred explanatory power.

A second contribution was made by:

presenting an example of ABM for socio-technical transition management.

This research presents a new example of sustainable material management and contributes to a growing field of socio-technical transition simulation studies (Bergman et al., 2008; Haxeltine et al., 2008; van Dam et al., 2013). Modelling socio-technical transition pathways is considered a promising tool to assess potential pathways leading to more sustainable regime configurations (Geels & Schot, 2007; Rotmans & Loorbach, 2009). The results highlight the co-evolution of regime items in socio-technical transitions, as user practices (i.e. demand) change depending on their knowledge and experience (e.g. option awareness and references), cultural and symbolic meaning (i.e. image and trends), and infrastructure (i.e. available materials from structural and civil engineering stock). While previous studies argued such co-evolution qualitatively (e.g. Foxon, 2011; Unruh, 2002) this study demonstrates and quantifies co-evolving regimes in a socio-technical model.

The third contribution can be summarized as:

integrating LCA and ABM for dynamic and systemic assessment.

Integrating LCA and ABM goes in the direction of a dynamic LCA where a dynamic foreground system (e.g. agent-based supply and demand model) is linked to an LCI background system (Davis, Nikolić, & Dijkema, 2009). In contrast to most traditional LCA studies, which assess individual products or services at one point in time, such combination allows for evaluating environmental impacts over time and at a system level. For example, the assessment of the environmental impact reduction over a whole system under different scenarios, and implication of potential extreme scenarios (e.g. complete reuse with higher aggregate substitution rates) is possible.

5.1.2 Case study: Sustainable construction materials management

To the case study of sustainable construction materials management in Switzerland this research contributed with the following three aspects: First, by:

revealing construction stakeholders' preferences and decision mechanisms.

We found that whereas in CE RMCM were broadly accepted they were still niche products in SE. In both construction sectors, awarding authorities' initial project specification for sustainable construction had little relevance to the subsequent material specific decision. It was the engineers' design specifications, which stood at the origin of material specific decisions, which showed significantly higher preferences for RMCM in CE. All subsequent decisions were primarily influenced by the interaction criteria. That was the reason why stakeholders in SE involved later in the chain usually followed the engineers' recommendation and mainly preferred conventional materials.

A second contribution was made through:

policy recommendation to enhance the demand for RMCM.

This research shows that the most effective interventions for a transition towards closed-loop mineral construction material management are extensive information campaigns, as already proposed by Spoerri et al. (2009), combined with small price incentives. The campaigns should primarily address the construction experts (e.g. architects and engineers) and inform about the option of recycled materials, their established standards, and relation to sustainable construction in general (e.g. through labels (Minergie, 2014)). In combination with small price incentives (about 5%) information campaigns might be sufficient to significantly enhance the use of recycled materials.

Still, simulation results imply that even such high RC demand fraction of almost 70% is insufficient for a complete reuse of C&D waste streams. A complete reuse would require a shift towards recycled concrete as a standard or higher aggregate substitution rates. This might lead to unintended consequences though, as environmental impacts might increase due to larger transport distances and higher cement demand required to produce recycled concrete of the same quality as conventional concrete with increased aggregate substitution. However, since these adverse effects might only apply for a minority of the applications (i.e. remaining 30%), from a systemic perspective a closed-loop recycling system would still be environmentally beneficial compared to the current system dominated by conventional concrete.

Third, this research contributes with:

clear recommendation regarding a sustainable application of RC.

C&D waste reuse in high-grade structural concrete applications has not only the potential to conserve natural gravel resources and limit waste streams to landfills but also to mitigate wider environmental impacts. This study demonstrated that RC reduces the environmental impacts to about 70% of the CC impacts if co-products from the recycling process are in the scope. This is at least partly in contrast to previous studies which showed equal or even higher environmental impacts of RC compared to CC (Holcim, 2010; Marinkovic et al., 2010). However, while cement production is still the main contributor, considering benefits from recovered steel scrap, avoided transport of C&D waste to the deposition site and avoided impacts of C&D waste disposal shifts the balance in favour of RC. Exclusion of these processes explained some of the differences to previous studies. If the additional amount of cement used for RC is limited to about 10% the impact is in a comparable range. While C&D waste composition has little influence on the results, additional transport for RC above 15km starts to shift the balance again for GWP. These thresholds have been used as recommendations for a sustainable application of RC directly addressing policy and industrial decision-makers.

5.2 Open issues and further research

Agent-based modelling: The broad range of ABM application, from highly context specific "case-based models" to generalizable "theoretical abstractions", influences the type of empirical data and validation methods required (Boero & Squazzoni, 2005; Janssen & Ostrom, 2006). Since the agent operationalization approach was developed in a highly context specific ABM application where agent decisions required a great deal of cognitive effort, its generalizability is limited. The adaptation of the proposed approach for operationalizing agents to "theoretical abstractions" will therefore be the subject for further research. The approach should also be adapted for ABM applications with more informal social interaction and less cognisant decisions. Once implemented, the fact that the most sensitive parameters had little empirical foundation clearly advocates more model iterations and early simulation runs with dummy data. Analysing how to balance the effort on modelling and empirical data collection in relation to model results might therefore be a promising strand of further research for context specific ABM developments.

Socio-technical transitions: The model developed in this research captured most key aspects of socio-technical transitions as outlined by Geels (2002, 2005). In particular user practices (i.e. construction stakeholders' material preferences), techno-specific knowledge (i.e. option awareness and experience), and cultural and symbolic meaning (i.e. image and trends) were modelled bottom-up. Other regime items such as technologies (i.e. applicable materials), sectorial policies (i.e. norms and standards), industrial networks (i.e. material supply and demand networks), and infrastructure (i.e. structural and civil engineering stock) were modelled top-down as exogenous variables influencing individual agent behaviour. But these regime items might also emerge from individual agent behaviour, for example new supply networks might emerge from growing demand. Further, with increasing market penetration of RMCM the technology grows out of the niche and will consequently benefit from economies of scale. Future research might therefore study how to model the interaction of a complete set of regime items from the bottom up and how they outgrow the niche to become the mainstream technology.

Life cycle assessment: The integration of LCA and ABM results provides a first step toward more systemic, dynamic and consequential environmental impact assessments. However, the static attributive inventories used in this research are expected to change over time as the foreground system might significantly alter the processes in the background system (e.g. changing compositions of C&D waste). In addition, due to the long lifetime of mineral construction materials consequential approaches might be more adequate but require further system expansion (e.g. indirect impact of land-use transformation). Therefore, the effect of static vs. dynamic LCI, attributive vs. consequential study designs, and integrated foreground and background systems, on LCA results is yet unclear and a promising route for future research (e.g. Hecher, Posch, Binder, & Knoeri, 2014; Miller, Moysey, Sharp, & Alfaro, 2013; Reap, Roman, Duncan, & Bras, 2008).

Construction material management: Supplies of RMCM from C&D waste, as well as the demand for concrete applications strongly depend on future construction activity. Linking both to construction investment scenarios allowed assessment of the alignment of supply and demand to a certain extent independently of construction activity. However, if the type of future construction investments started to changes, for example demolition and replacement becomes the mainstream investment into the building stock, C&D waste volumes will more dramatically increase and more extreme measures might be required for closed-loop material management. In this research the decisions leading to new-construction, renovation or demolition of the built environment were all simplified by means of construction investment. Therefore, an in-depth analysis and modelling of these decisions might be a promising strand of future work (Friege & Chappin, 2014; Knoeri, Goetz, & Binder, 2014).

6 Conclusion

A transition towards sustainable construction materials management presents one of the bigger challenges of the 21st century, with construction materials among the most heavily consumed commodities globally, significant carbon implications of cement production, and increasing construction & demolition (C&D) waste streams. Reusing C&D waste as recycled mineral construction materials (RMCM) has been considered as a valuable option to substitute primary aggregates, to reduce C&D waste deposition where space for landfills is increasingly scarce, and to reduce associated environmental impacts.

However, besides the large and increasing amounts of C&D waste and proven and standardised technical feasibility RMCM are not yet broadly accepted nor applied. Furthermore, from an ecological perspective it was not clear whether RMCM have environmental benefits compared to conventional materials and if reuse is the most suitable treatment of C&D waste.

In this thesis, these issues were addressed from a systemic perspective including technical (i.e. material flows), socio-economic (i.e. stakeholders' decisions and interaction), and ecological aspects (i.e. environmental impacts) and sustainable construction material management was conceptualised as a socio-technical transition.

This research achieved its objective of developing a simulation tool to analyse transitions towards a more sustainable construction material management. Specifically, it (i) demonstrated the large supply potential of C&D waste for RMCM, (ii) revealed actors' decisions and interaction about the demand for RMCM, (iii) showed that targeted information campaigns combined with small price incentives are sufficient to significantly enhance the demand for RMCM, and (iv) substantiated environmental benefits of RMCM compared to conventional materials. Based on these findings specific recommendations for sustainable construction material management were developed and communicated to industrial stakeholders, and policy makers. Further, this research contributed to the methodological development of agent-based modelling (ABM) by developing an agent-operationalisation approach, providing a context specific agent-based model of a socio-technical transition, and integrating ABM and life cycle assessment.

In summary, this research showed that a systemic assessment of complex socio-technical transitions generates a new quality of results. In particular the integration of different methods, analysing demand and supply and related environmental impacts, revealed new insights as well as open issues for further research at the cross section of methods applied. This comprehensive analysis demonstrated that C&D waste stream could be almost completely reused for RMCM in the Swiss case study, which would be achievable through extensive information campaigns, but under current norms and standards, while significantly reducing the associated environmental impacts. Therefore, C&D waste reuse for RMCM present a valuable transition pathway toward a more sustainable construction material management.

7 References

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes, 50*(2), 179-211.

Althaus, H. J., Dinkel, F., Stettler, C., & Werner, F. (2007). Life Cycle Inventories of Renewable Materials *Final report ecoinvent v2.0 No. 21*. Duebendorf, CH: Swiss Centre for Life Cycle Inventories.

Amihud, Y., & Lev, B. (1981). Risk reduction as a managerial motive for conglomerate mergers. *Bell Journal of Economics, 12*(2), 605-617.

Andrews, C. J., Yi, D., Krogmann, U., Senick, J. A., & Wener, R. E. (2011). Designing Buildings for Real Occupants: An Agent-Based Approach. *Ieee Transactions on Systems Man and Cybernetics Part a-Systems and Humans, 41*(6), 1077-1091.

Axelrod, R. (1997a). Advancing the art of simulation in the social sciences. In R. Conte, R. Hegselmann & P. Terna (Eds.), *Simulating social phenomena* (pp. 21-40). Berlin: Springer-Verlag.

Axelrod, R. (1997b). *The complexity of cooperation: Agent-based models of competition and collaboration*. Princeton: Princeton University Press.

Axtell, R. L., Andrews, C. J., & Small, M. J. (2001). Agent-Based Modeling and Industrial Ecology. *Journal of Industrial Ecology, 5*(4), 10-13.

Baccini, P., & Brunner, P. H. (2012). *Metabolism of the Anthroposphere: Analysis, Evaluation, Design* (2 ed.): MIT Press.

Bergman, N., Haxeltine, A., Whitmarsh, L., Kohler, J., Schilperoord, M., & Rotmans, J. (2008). Modelling socio-technical transition patterns and pathways. *Journal of Artificial Societies and Social Simulation, 11*(3), 1460-7425.

Bergsdal, H., Brattebo, H., Bohne, R. A., & Mueller, D. B. (2007). Dynamic material flow analysis for Norway's dwelling stock. *Building Research and Information, 35*(5), 557-570.

Berkhout, F. (2002). Technological regimes, path dependency and the environment. *Global Environmental Change-Human and Policy Dimensions, 12*(1), 1-4.

Binder, C. R. (2005). *Concept and models on material stocks and flows in human-environment systems: A contribution to transitions towards sustainable development.* (Habilitation thesis), Swiss Federal Institute of Technology, Zurich.

Binder, C. R. (2007). From material flow analysis to material flow management Part II: the role of structural agent analysis. *Journal of Cleaner Production, 15*(17), 1605-1617.

Binswanger, H. C., & Siegenthaler, C. P. (1995). Towards an Ecologically and Economically Reasonable Management of Mineral-Resources. *Eclogae Geologicae Helvetiae, 88*(2), 421-434.

Blum, A., & Stutzriemer, S. (2007). Recycled construction minerals for urban infrastructure in Germany: non-technical issues., *Minerals & Energy*(3-4), 148-158.

Boero, R., & Squazzoni, F. (2005). Does Empirical Embeddedness Matter? Methodological Issues on Agent-Based Models for Analytical Social Science. *Journal of Artificial Societies and Social Simulation, 8*(4), 1460-7425.

Bollinger, L. A., Davis, C., Nikolić, I., & Dijkema, G. P. J. (2011). Modeling Metal Flow Systems. *Journal of Industrial Ecology*.

Busenitz, L. W., & Barney, J. B. (1997). Differences between entrepreneurs and managers in large organizations: Biases and heuristics in strategic decision-making. *Journal of Business Venturing, 12*(1), 9-30.

Cabral, A., Schalch, V., Carpena, D., & Duarte, J. (2010). Mechanical properties modeling of recycled aggregate concrete. *Construction and Building Materials, 24*, 421–430.

Carpenter, A. C., Gardner, K. H., Fopiano, J., Benson, C. H., & Edil, T. B. (2007). Life cycle based risk assessment of recycled materials in roadway construction. *Waste Management, 27*(10), 1458-1464.

Cassina, E., Plüss, P., Sutter, J., Angst, C., & Kronig, M. (2002). Stoffliche Zusammensetzung und Beurteilung der langfristigen Umweltverträglichkeit von Sekundärbaustoffen: Vereinigung schweizerischer Strassenfachleute (VSS).

Cedermann, L.-E. (2005). Computational models of social forms; advancing generative process theory. *American Journal of Sociology, 110*(4), 864-893.

Chappin, E. J. L., & Dijkema, G. P. J. (2010). Agent-based modelling of energy infrastructure transitions. *International Journal of Critical Infrastructures, 6*(2), 106-130.

Chiu, C.-T., Hsu, T.-H., & Yang, W.-F. (2008). Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. *Resources, Conservation and Recycling, 52*(3), 545-556.

Davis, C., Nikolic, I., & Dijkema, G. P. J. (2010). Industrial Ecology 2.0. *Journal of Industrial Ecology, 14*(5), 707-726.

Davis, C., Nikolić, I., & Dijkema, G. P. J. (2009). Integration of Life Cycle Assessment Into Agent-Based Modeling. *Journal of Industrial Ecology, 13*(2), 306-325.

Doka, G. (2000). *Ökoinventar der Entsorgungsprozesse von Baumaterialien, Grundlagen zur Integration der Entsorgung in Ökobilanzen von Gebäuden. Untersuchung im Rahmen des IEA BCS Annex 31: Energy Related Environmental Impact of Buildings* (Vol. 1. Auflage). Zürich: Bundesamt für Energie (BFE).

Doka, G. (2007). Life cycle inventories of waste treatment services. Final report EcoInvent data v 2.0, n°13. Dübendorf, Switzerland: Swiss Centre for Life Cycle Inventories.

Duran, X., Lenihan, H., & O'Regan, B. (2006). A model for assessing the economic viability of construction and demolition waste recycling - the case of Ireland. *Resources Conservation and Recycling, 46*(3), 302-320.

Eberhard. (2014). Baustoffe 2014. Retrieved 09.06.2014, from http://www.eberhard.ch/dnl/104_1275_RC_Primaerbaustoffe_Peisliste_2014-2.pdf

Epstein, J. M., & Axtell, R. (1996). *Growing artificial societies: social science from the bottom up*. Washington, D.C: Brookings Institution Press.

Fatta, D., Papadopoulos, A., Avramikos, E., Sgourou, E., Moustakas, K., Kourmoussis, F., Mentzis, A., & Loizidou, M. (2003). Generation and management of construction and demolition waste in Greece - an existing challenge. *Resources Conservation and Recycling, 40*(1), 81-91.

Faust, K. (1997). Centrality in affiliation networks. *Social Networks, 19*(2), 157-191.

Finucane, M. L., Alhakami, A., Slovic, P., & Johnson, S. M. (2000). The affect heuristic in judgments of risks and benefits. *Journal of Behavioral Decision Making, 13*(1), 1-17.

Fischer-Kowalski, M., & Haberl, H. (2007). *Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use*. Northhampton, MA: Edward Elgar.

FOEN. (2001a). Bauabfälle Schweiz - Mengen, Perspektiven und Entsorgungswege. Band 1: Kennwerte *Umwelt-Materialien* (Vol. 131). Bern: Federal Office for the Environment (FOEN).

FOEN. (2001b). Bauabfälle Schweiz - Mengen, Perspektiven und Entsorgungswege. Band 2: Kantonale Werte *Umwelt-Materialien*. Bern: Federal Office for the Environment (FOEN).

FOEN. (2004). Abfallstatistik 2002: Mit Daten der KVA Planung 2003 *Umwelt-Materialien Abfall*. Bern: Federal Office for the Environment (FOEN).

FOEN. (2005). An overview on waste amounts and recycling in 2004. Bern: Federal Office for the Environment (FOEN).

FOEN. (2006). Richtlinie für die Verwertung mineralischer Bauabfälle (Ausbauasphalt, Strassenaufbruch, Betonabbruch, Mischabbruch). Bern: Federal Office for the Environment (FOEN).

FOEN. (2008). Bauabfaelle Hochbau in der Schweiz; Ergebnisse der Studie 2008. Bern, Switzerland: Federal Office for the Environment.

Fonseca, N., de Brito, J., & Evangelista, L. (2011). The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste. *Cement & Concrete composites, 33*, 637 – 643.

Foxon, T. J. (2011). A coevolutionary framework for analysing a transition to a sustainable low carbon economy. *Ecological Economics, 70*(12), 2258-2267.

Friege, J., & Chappin, E. (2014). Modelling decisions on energy-efficient renovations: A review. *Renewable and Sustainable Energy Reviews, 39*(0), 196-208.

FSO. (2010). Material flow accounts - Growth in society's stock of materials *Environmental Accounts*. Neuchâtel: Federal statistical Office (FSO).

Garcia, R. (2005). Uses of agent-based modeling in innovation/new product development research. *Journal of Product Innovation Management, 22*(5), 380-398.

Gardner, M. (1971). Cellular Automata, Self-Reproduction, Garden of Eden and Game Life. *Scientific American, 224*(2), 112-&.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy, 31*(8,Äì9), 1257-1274.

Geels, F. W. (2005). Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective. *Technological Forecasting and Social Change, 72*(6), 681-696.

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy, 36*(3), 399-417.

Giddens, A. (1984). *The constitution of the society*. Berkeley, CA: University of California Press.

Gilbert, N. (2008). *Agent-Based Models*. Los Angeles: Sage Publications.

Gilbert, N., & Troitzsch, K. G. (2005). *Simulation for the social scientist.* (2 ed.). Berkshire, England: Open University Press, McGraw-Hill.

Grimm, V., & Railsback, S. F. (2005). *Individual-based Modeling and Ecology*: Princeton University Press.

Hao, J. L., Hills, M. J., & Huang, T. (2007). A simulation model using system dynamic method for construction and demolition waste management in Hong Kong. *Construction Innovation, 7*(1), 7-21.

Hashimoto, S., Tanikawa, H., & Moriguchi, Y. (2007). Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. *Waste Management, 27*, 1725-1738.

HASTAG. (2014). Produkte und Preise 2014ß. Retrieved 09.06.2014, from http://www.hastag.ch/data/docs/download/8397/de/HASTAG-PL2014-light.pdf

Haxeltine, A., Withmarsh, L., Bergman, N., Rotmans, J., Schilperoord, M., & Kohler, J. (2008). A Conceptual Framework for transition modelling. *International Journal for Innovation and Sustainable Development, 3*(1/2).

Hecher, M., Posch, A., Binder, C., & Knoeri, C. (2014, 8. -10. September 2014). *Dynamic LCA of heating technologies applied in residential building stocks.* Paper presented at the 10. Ökobilanzwerkstatt: Ökobilanzielle Bewertung von Energietechnologien und Energiesystemen, Dresden.

Hiete, M., Stengel, J., Ludwig, J., & Schultmann, F. (2011). Matching construction and demolition waste supply to recycling demand: a regional management chain mode. *Building Research and Information, 39*(4), 333 – 351.

Hoffmann, C., Figi, R., & Leemann, A. (2006). Untersuchung der Grundwasserverträglichkeit von Magerbeton aus RC-Material. Zürich: Baudirektion Kanton Zürich, Amt für Abfall Wasser Energie und Luft (AWEL), Eidgenössische Material Prüfungs Anstalt (EMPA), Abteilung Beton / Bauchemie.

Hoffmann, C., & Jacobs, F. (2007). Recyclingbeton aus Beton- und Mischabbruchgranulat. Dübendorf: Material Science and Technology (EMPA), Abteilung Beton/Bauchemie und TFB, Technische Forschung und Beratung für Zement und Beton, Wildegg.

Hofmann, W., & Patt, B. (2006). Konstruktionen aus Mischabbruch. *tec21; Die Fachzeitschrift für Architektur, Ingenieurwesen und Umwelt, 10*, 8-10.

Holcim. (2010). Oekobilanzen rezyklierter Gesteinskörnung für Beton. Zurich: Holcim.

Holland, J. H. (1995). *Hidden Order: How Adaptation Builds Complexity*. Reading MA: Addison-Wesley.

Huang, Y., Bird, R. N., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources Conservation and Recycling, 52*(1), 58-73.
Hugener, M., Deschwanden, H., & Bähler, T. (1999). Umweltgerechtes Recycling von teerhaltigen Belägen. Teilprojekt 1: Erfassung des Status-Quo und Abklärung der Bedürfnisse. Dübendorf: EMPA Material Research and Testing.
Hugener, M., Emmenegger, L., & Mattrel, P. (2006). Zusammenhang zwischen PAK-Gehalt in teerhaltigem Recyclinggranulat und in den emittierten Dämpfen beim Wiedereinbau. Dübendorf: EMPA Material Research and Testing.
Hugener, M., Mattrel, P., Schmid, P., & Fritz, H. W. (1998). Recycling von Strassenbelägen - ein Umweltproblem? *Chimia, 52*, 225-229.
Huntzinger, D. N., & Eatmon, T. D. (2009). A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. *Journal of Cleaner Production, 17*(7), 668-675.
ISO. (2006a). ISO 14044; Environmental management - Life cycle assessment - Principals and framework (2 ed.): International Organization for Standardization (ISO).
ISO. (2006b). ISO 14044; Environmental management - Life cycle Assessment - Requirements and guidelines: International Organization for Standardization (ISO).
Jager, W., & Janssen, M. (2002, Jul 15-16). *The need for and development of behaviourally realistic agents.* Paper presented at the 3rd International Workshop on Multi-Agent-Based Simulation II (MABS 2002), Bologna, Italy.
Jang, Y. C., & Townsend, T. (2001). Sulfate leaching from recovered construction and demolition debris fines. *Advances in Environmental Research, 5*(3), 203-217.
Janssen, M. A. (2002). *Complexity and ecosystem management: the theory and practice of multi-agent systems*. Cheltenham: Elgar.
Janssen, M. A., & Ostrom, E. (2005). Governing social-ecological systems. In L. Tesfatsion & K. L. Judd (Eds.), *Handbook of computational economics II: agent-based computational economics*. Amsterdam, The Netherlands: Elsevier.
Janssen, M. A., & Ostrom, E. (2006). Empirically based, agent-based models. *Ecology and Society, 11*(2).
Jennings, N. R. (2000, 1999). *On agent-based software engineering.* Paper presented at the 16th International Joint Conference on Artificial Intelligence, Stockholm, Sweden.
Johnson, E. J., Payne, J. W., & Bettman, J. R. (1988). Information displays and preference reversals. *Organizational Behavior and Human Decision Processes, 42*(1), 1-21.
Jungermann, H., Pfister, H.-R., & Fischer, K. (1998). *Die Psychologie der Entscheidung: eine Einführung*. Heidelberg: Spektrum Akademischer Verlag.
KBOB. (2007). Beton aus recyclierter Gesteinskörnung *Empfehlung für nachhaltiges Bauen* (Vol. 2). Bern: Koordination der Bau und Liegenschaftsorgane des Bundes (KBOB).
Kellenberger, D., Althaus, H.-J., Künniger, T., Lehmann, M., Jungbluth, N., & Thalmann, P. (2007). Life Cycle Inventories of Building Products *Final report ecoinvent v2.0 No. 7*. Duebendorf, CH: Swiss Centre for Life Cycle Inventories.
Kind, E., Müller, E., Vogt, L., & Suter, B. (2006). *Kieshaushalt Schweiz: Eine ökonomische Betrachtung.* (Semesterarbeit), ETH Zürich, Zürich.
Knoeri, C., Binder, C. R., & Althaus, H. J. (2011a). An agent operationalization approach for context specific agent-based modeling. *JASSS The Journal of Artificial Societies and Social Simulation, 14*(2).
Knoeri, C., Binder, C. R., & Althaus, H. J. (2011b). Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials. *Resources, Conservation and Recycling, 55*(11), 1039-1050.
Knoeri, C., Goetz, A., & Binder, C. R. (2014, 1.-5. 09.). *Generic bottom-up building-energy models for developing regional energy transition scenarios.* Paper presented at the 9th Conference of the European Social Simulation Association, Barcelona, Spain
Knoeri, C., Nikolic, I., Althaus, H. J., & Binder, C. R. (2014). Enhancing Recycling of Construction Materials: An Agent Based Model with Empirically Based Decision Parameters. *Journal of Artificial Societies and Social Simulation, 17*(3).

Knoeri, C., Sanyé-Mengual, E., & Althaus, H. J. (2013). Comparative LCA of recycled and conventional concrete for structural applications. *International Journal of Life Cycle Assessment, 18*(5), 909-918.

Kohler, N., Altmann, K., Barth, B., Bedell, J., Hollinger, M., Kukul, E., Leuridan, Y., Schukraft, R., & Luützkendorf, T. (1994). *Energie- und Stoffbilanzen von Gebäuden während ihrer Lebensdauer*. Bern: ENET.

Kohler, N., Hassler, U., & Paschen, H. (1999). *Stoffströme und Kosten in den Bereichen Bauen und Wohnen*. Berlin, Heidelberg, New York: Springer-Verl.

Küppers, G., & Lenhard, J. (2005). Validation of Simulation: Pattern in the social and Natural Science. *Journal of Artificial Societies and Social Simulation, 8*(4).

Langton, C. G. (1987). *Artificial Live.* Paper presented at the Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems, Los Alamos, NM, USA.

Lawson, N., Douglas, I., Garvin, S., McGrath, C., Manning, D., & Jonathan, V. (2001). Recycling construction and demolition wastes - a UK perspective. *Environmental Management and Health, 12*(2), 146 - 157

Lenzen, M. (1998). Primary energy and greenhouse gases embodied in Australian final consumption: an input-output analysis. *Energy Policy, 26*(6), 495-506.

Li, X. (2008). Recycling and reuse of waste concrete in China: Part I. Material behaviour of recycled aggregate concrete. *Resources, Conservation and Recycling, 53*(1-2), 36-44.

Lichtensteiger, T. (1998). *Ressourcen am Bau: Aspekte einer nachhaltigen Ressourcenbewirtschaftung im Bauwesen*. Zürich: vdf Hochschulverlag AG der ETH Zürich.

Lichtensteiger, T. (2006). *Bauwerke als Ressourcennutzer und Ressourcenspender, in der langfristigen Entwicklung urbaner Systeme; Ein Beitrag zur Exploration urbaner Lagerstätten*. Zürich: vdf Hochschulverlag AG an der ETH Zürich.

Limbachiya, M. C., Marrocchino, E., & Koulouris, A. (2007). Chemical-mineralogical characterisation of coarse recycled concrete aggregate. *Waste Management, 27*(2), 201-208.

Ling, Y. Y. (2002). A conceptual model for selection of architects by project managers in Singapore. *International Journal of Project Management, 21*(2003), 135-144.

Loughlin, D. H., & Barlaz, M. A. (2006). Policies for Strengthening Markets for Recyclables: A Worldwide Perspective. *Critical Reviews in Environmental Science and Technology, 36*(4).

Louie, M. A., & Carley, K. M. (2008). Balancing the criticisms: Validating multi-agent models of social systems. *Simulation Modelling Practice and Theory, 16*(2), 242-256.

Malaska, P. (1994). Progress, nature and technology in late-modern transition. *Futures, 26*, 529-542.

Marinkovic, S., Radonjanin, V., Malesev, M., & Ignjatovic, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management, 30*(11), 2255-2264.

Martens, P., & Rotmans, J. (2005). Transitions in a globalising world. *Futures, 37*(10), 1133-1144.

Matthews, R. B., Gilbert, N. G., Roach, A., Polhill, J. G., & Gotts, N. M. (2007). Agent-based land-use models: a review of applications. *Landscape Ecology, 22*(10), 1447-1459.

Mercante, I., Bovea, M., Ibáñez-Forés, V., & Arena, A. (2011). Life cycle assessment of construction and demolition waste management systems: a Spanish case study. *International Journal of Life Cycle Assessment, 17*(2), 232-241.

Miller, S. A., Moysey, S., Sharp, B., & Alfaro, J. (2013). A Stochastic Approach to Model Dynamic Systems in Life Cycle Assessment. *Journal of Industrial Ecology, 17*(3), 352-362.

Minergie. (2014). Minergie-Eco. Retrieved 09.06.2014, from http://www.minergie.ch/minergie-ecop-eco.html

Minsky, M. (1968). Theory of computation. *American Mathematical Monthly, 75*(4).

Moser, K., Bertschinger, H., Hugener, M., Richner, P., & Richter, K. (2004). Baustoffmanagement 21 an der EMPA, Stand des Wissens und Forschungsbedarf: Material Science and Technology (EMPA).

Mosler, H.-J., & Tobias, R. (2005). *Simulation of collective action based on empirical data.* Paper presented at the 2nd International Conference of the European Social Simulation Association, Valladolid, Spain.

Moss, S. (2008). Alternative Approaches to the Empirical Validation of Agent-Based Models. *Journal of Artificial Societies and Social Simulation, 11*(15).

Muller, D. B. (1998). *Modellierung, Simulation und Bewertung des regionalen Holzhaushaltes: Untersuchung zur Wald- und Holzbewirtschaftung in einer nachhaltigen Regionalentwicklung.* (Dissertation Nr. 12990), ETH Zürich Zürich.

Muller, D. B. (2006). Stock dynamics for forecasting material flows - Case study for housing in The Netherlands. *Ecological Economics, 59*(1), 142-156.

Nakamura, S., & Kondo, Y. (2002). Input-output analysis of waste management. *Journal of Industrial Ecology, 6*(1), 39-63.

Nikolic, I. (2009). *Co-evolutionary method for modelling large scale socio-technical systems evolution* (M. P. C. Weijnen & G. P. J. Dikema Eds.). Delft, The Netherlands: Next Generation Infrastructures Foundation.

Page, B. (1991). *Diskrete Simulation: Eine Einführung mit Modula-2*. Berlin, Heidelberg, New York: Springer-Verl.

Parker, C., Manson, S. M., Janssen, M. A., Hoffmann, M. J., & Deadman, P. (2003). Multi-agent systems for the simulation of land-use and land-cover change; a review. *Annals of the Association of American Geographers, 93*(2), 314-337.

Pettigrew, A. M. (1973). *The Politics of Organizational decision-making*. London: Tavistock.

Polhill, J. G., Parker, D., Brown, D., & Grimm, V. (2008). Using the ODD Protocol for Describing Three Agent-Based Social Simulation Models of Land-Use Change. *Jasss-the Journal of Artificial Societies and Social Simulation, 11*(2).

Poon, C. S. (2007). Management of construction and demolition waste. *Waste Management, 27*(2), 159-160.

Poon, C. S., Kou, S.-c., Wan, H.-w., & Etxeberria, M. (2009). Properties of concrete blocks prepared with low grade recycled aggregates. *Waste Management, 29*(8), 2369-2377.

Rahmandad, H., & Sterman, J. (2008). Heterogeneity and network structure in the dynamics of diffusion: Comparing agent-based and differential equation models. *Management Science, 54*(5), 998-1014.

Ramanath, A. M., & Gilbert, N. (2004). The design of participatory agent-based social simulations. *Jasss-the Journal of Artificial Societies and Social Simulation, 7*(4).

Rao, A., Jha, K. N., & Misra, S. (2007). Use of aggregates from recycled construction and demolition waste in concrete. *Resources, Conservation and Recycling, 50*(1), 71-81.

Reap, J., Roman, F., Duncan, S., & Bras, B. (2008). A survey of unresolved problems in life cycle assessment. *The International Journal of Life Cycle Assessment, 13*(4), 290-300.

Redle, M. (1999). *Kies- und Energiehaushalt urbaner Regionen in Abhängigkeit der Siedlungsentwicklung.* (Dissertation Nr. 13108), ETH Zürich Zürich.

Reynolds, C. W. (1987). Flocks, herds, and schools: a distributed behavioral model. *Computer Graphics (SIGGRAPH '87 Conference Proceedings), 21*(4), 25-34.

Robin, C. P. Y., & Poon, C. S. (2009). Cultural shift towards sustainability in the construction industry of Hong Kong. *Journal of Environmental Management, 90*(11), 3616-3628.

Robinson, G. R., Menzie, W. D., & Hyun, H. (2004). Recycling of construction debris as aggregate in the Mid-Atlantic Region, USA. *Resources Conservation and Recycling, 42*(3), 275-294.

Rotmans, J., & Loorbach, D. (2009). Complexity and Transition Management. *Journal of Industrial Ecology, 13*(2), 184-196.

Saaty, T. L. (1990). How to Make a Decision - the Analytic Hierarchy Process. *European Journal of Operational Research, 48*(1), 9-26.

Sani, D., Moriconi, G., Fava, G., & Corinaldesi, V. (2005). Leaching and mechanical behaviour of concrete manufactured with recycled aggregates. *Waste Management, 25*, 177-182.

Sargent, R. G. (1982). Verification and Validation of Simulation Models. In F. E. Cellier (Ed.), *Progress in Modelling and Simulation* (pp. 159-169). London: Academic Press.

Sargent, R. G. (2008, Dec 09-12). *Verification and validation of simulation models.* Paper presented at the 2008 Winter Simulation Conference, Washington, DC.

Schachermayer, E., Lahner, T., & Brunner, P. H. (2000). Assessment of two different separation techniques for building wastes. *Waste Management & Research, 18*(1), 16-24.

Schelling, T. (1978). *Micromotives and Macrobehavior*. New York: W W Norton & Co Ltd.

Schneider, M., & Rubli, S. (2007). Ressourcenmodell mineralischer Baustoffe auf der Ebene Stadt Zürich. Zürich: Amt für Hochbauten der Stadt Zürich, Tiefbauamt der Stadt Zürich.

Schneider, M., & Rubli, S. (2009). Ressourcenmodell der mineralischen Baustoffe auf der Ebene Stadt Zürich; Dynamische Modellierung 1995–2050. Zürich: Tiefbauamt der Stadt Zürich, Amt für Hochbauten der Stadt Zürich.

Scholz, R. W., & Tietje, O. (2002). *Embedded case study methods; Integrating quantitative and qualitative knowledge*. Thousand Oaks: Sage Publications.

Schwarz, N., & Ernst, A. (2009). Agent-based modeling of the diffusion of environmental innovations - An empirical approach. *Technological Forecasting and Social Change, 76*(4), 497-511.

SIA. (1994). SIA 162/4, SN 562 162/4 Recyclingbeton: Schweizerischer Ingenieur und Architekten Verein (SIA), Schweizer Norm (SN).

SIA. (2010). SIA 2030 Recyclingbeton (2 ed.): Schweizerischer Ingenieur und Architekten Verein (SIA), Schweizer Norm (SN).

Spoerri, A. (2006). Nachhaltige Bewirtschaftung von mineralischen Rückbaustoffen: 1. Zwischenbericht: Systemanalyse. Zürich: ETH Zürich, Natural and Social Science Interface.

Spoerri, A., Lang, D. J., Binder, C. R., & Scholz, R. W. (2009). Expert-based scenarios for strategic waste and resource management planning - C&D waste recycling in the Canton of Zurich, Switzerland. *Resources, Conservation and Recycling, 53*(10), 592-600.

Stachowiak, H. (1973). *Allgemeine Modelltheorie [General Modelling Theory]*. Berlin: Springer.

Svenson, O. (1979). Process Descriptions of Decision-Making. *Organizational Behavior and Human Performance, 23*(1), 86-112.

Svenson, O. (1990). *Some propositions for the classification of decision situations*. Amsterdam: Elsevier Science.

Svenson, O. (1996). Decision making and the search for fundamental psychological regularities: What can be learned from a process perspective? *Organizational Behavior and Human Decision Processes, 65*(3), 252-267.

Tam, V. W. Y., Gao, X. F., & Tam, C. M. (2006). Environmental enhancement through use of recycled aggregate concrete in a two-stage mixing approach. *Human and Ecological Risk Assessment, 12*(2), 277-288.

Tanner, I. (2005). *Dynamische Modellierung des Potentials von Sekundärrohstoffen aus Strassen.* (Diplomarbeit), ETH Zürich, Zürich.

Tesfatsion, L. (2002). Agent-based computational economics: Growing economies from the bottom up. *Artificial Life, 8*(1), 55-82.

Tesfatsion, L., & Judd, K. L. (2006). *Handbook of computational economics: agent-based computational economics* (Vol. 2). Amsterdam: Elsevier.

Uebersax, H. (2005). Kies für Generationen: Kommunikation. Zürich: Amt für Abfall, Wasser, Energie und Luft des Kanton Zürich; Abt. Abfall.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy, 28*(12), 817-830.

Unruh, G. C. (2002). Escaping carbon lock-in. *Energy Policy, 30*(4), 317-325.
van Dam, K. H., Nikolic, I., & Lukszo, Z. (2013). *Agent-Based Modelling of Socio-Technical Systems* (Vol. 9): Springer, Netherlands.
van Oss, H. G., & Padovani, A. C. (2003). Cement manufacture and the environment, Part II: Environmental challenges and opportunities. *Journal of Industrial Ecology, 7*(1), 93-126.
Vester, F. (2007). *The art of interconnected thinking: Tools and concepts for a new approach to tackling complexity*. Munich, Germany: MCB.
VSS. (1998a). SN 670 062 Recycling; Allgemeines: Vereinigung-Schweizerischer-Strassenfachleute (VSS), Schweizer-Norm (SN).
VSS. (1998b). SN 670 141 Recycling; Ausbauasphalt: Vereinigung-Schweizerischer-Strassenfachleute (VSS), Schweizer Norm (SN).
VSS. (1998c). SN 670 142 Recycling; Strassenaufbruch: Vereinigung-Schweizerischer-Strassenfachleute (VSS), Schweiizer Norm (SN).
VSS. (1998d). SN 670 143 Recycling; Betonabbruch: Vereinigung-Schweizerischer-Strassenfachleute (VSS), Schweizer Norm (SN).
VSS. (1998e). SN 670 144 Recycling; Mischabbruch: Vereinigung-Schweizerischer-Strassenfachleute (VSS), Schweizer Norm (SN).
Wasserman, S., & Faust, K. (1994). *Social Network Analysis: Methods and Applications* Cambridge Univ. Press.
WBCDS. (2009). The Cement Sustainability Initiative - Concrete recycling. Geneva: World Business Council for Sustainable Development (WBCDS).
Weibel, T., & Stritz, A. (1995). Oekoinventare und Wirkungsbilanzen von Baumaterialien; Grundlagen für den ökologischen Vergleich von Hochbaukonstruktionen *ESU-Reihe*: ETH Zürich.
Weil, M., Jeske, U., & Schebek, L. (2006). Closed-loop recycling of construction and demolition waste in Germany in view of stricter environmental threshold values. *Waste Management & Research, 24*(3), 197-206.
Werner, F., Althaus, H.-J., Künniger, T., Richter, K., & Jungbluth, N. (2007). Life Cycle Inventories of Wood as Fuel and Construction Material *Final report ecoinvent v2.0 No. 9*. Duebendorf, CH: EMPA Duebendorf, Swiss Centre for Life Cycle Inventories.
Wiedmann, T., Minx, J., Barrett, J., & Wackernagel, M. (2006). Allocating ecological footprints to final consumption categories with input-output analysis. *Ecological Economics, 56*(1), 28-48.
Windrum, P., Fagiolo, G., & Moneta, A. (2007). Empirical Validation of Agent-Based Models: Alternatives and Prospects. *Journal of Artificial Societies and Social Simulation, 10*(2).
Witt, U. (1997). ''Lock-in'' vs. ''critical masses'' - industrial change under network externalities. *International Journal of Industrial Organization, 15*(6), 753-773.
Woodward, R., & Duffy, N. (2011). Cement and concrete flow analysis in a rapidly expanding economy: Ireland as a case study. *Resources, Conservation and Recycling, 55*, 448–455.
Wooldridge, M., & Jennings, N. R. (1995). Intelligent Agents - Theory and Practice. *Knowledge Engineering Review, 10*(2), 115-152.
World Commission on Environment and Development. (1987). *Our common future*. Oxford; New York: Oxford University Press.
Worrell, E., Price, L., Martin, N., Hendriks, C., & Meida, L. O. (2001). Carbon dioxide emissions from the global cement industry. *Annual Review of Energy and the Environment, 26*(1), 303-329.

Part B – Manuscripts

List of manuscripts

Publication I

Knoeri, C., Binder, C. R., & Althaus, H. J. (2011). An agent operationalization approach for context specific agent-based modelling. *JASSS The Journal of Artificial Societies and Social Simulation, 14(2).*

http://jasss.soc.surrey.ac.uk/14/2/4.html

Publication II

Knoeri, C., Binder, C. R., & Althaus, H. J. (2011). Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials. *Resources, Conservation and Recycling, 55(11), 1039-1050.*

DOI: 10.1016/j.resconrec.2011.05.018

Publication III

Knoeri, C., Nikolić, I., Althaus, H. J., & Binder, C. (2014). Enhancing recycling of construction materials: an agent based model with empirically based decision parameters. *JASSS The Journal of Artificial Societies and Social Simulation, 17(3).*

http://jasss.soc.surrey.ac.uk/17/3/10.html

Publication IV

Knoeri, C., Sanyé-Mengual, E., & Althaus, H. J. (2013). Comparative LCA of recycled and conventional concrete for structural applications. *International Journal of Life Cycle Assessment, 18*(5), 909-918.

DOI: 10.1007/s11367-012-0544-2

Publication I

An agent operationalization approach for context specific agent-based modelling

Overview

This paper presents an operationalization approach to determine the key system agents, their interactions, decision-making and behaviours for context specific agent-based modelling (ABM). It thus addresses three major concerns limiting the full exploitation of ABM’s potential; (i) agents are modelled too simple and behave unrealistically with little empirical basis, (ii) 'proof of concept' applications are too theoretical and (iii) too much value is placed on operational validity instead of conceptual validity. Results from the Swiss mineral construction material case study illustrate the data, which can be derived by applying the proposed approach and demonstrate it’s practicability for context specific agent-based model development.

Main findings

The approach addresses three major concerns limiting ABMs' full potential:

- Going beyond a "proof of concept": The approach gives a specific strategy for embedding empirical knowledge into modelling practices. It provides a step-by-step procedure for identifying the relevant agents to be included in ABM, and for analysing their interaction chain in participatory approaches (e.g. expert interviews and workshops), thus enhancing the credibility of models implemented.

- Behaviourally realistic agents: The approach provides an array of sample agents with realistic (i.e. empirically quantified) decision-making and behaviour. This significantly reduces the parameter space to scan in an agent-based model. Quantifying agents' decisions with AHP provides not only a set of directly implementable decision-making data but also an opportunity to test consistency in decision-making empirically. In addition, comparing the decision-making outcome with reported behaviour allows one to further validate/falsify the implemented decision-making theory.

- Conceptual validity: The approach enhances the importance of conceptual model validity by providing a way to empirically test one's theoretical assumptions.

Relevance for the doctoral thesis

The agent operationalization approach provided the conceptual framework and the step-by-step procedure for empirically operationalizing agents in the dissertation.

An agent operationalization approach for context specific agent-based modeling

Christof Knoeri [1,2], Claudia R. Binder [3] , Hans-Joerg Althaus [2]

1) Department of Geography, University of Zürich, CH-8057 Zürich, Switzerland, chritof.knoeri@empa.ch
2) Technology and Society Laboratory, Empa, CH-8600 Duebendorf, Switzerland, hans-joerg.althaus@empa.ch

3) *Institute of Systems Sciences, Innovation and Sustainability Research (ISIS), University of Graz, 8010 Graz, Austria, claudia.binder@uni-graz.at*

Journal of Artificial Societies and Social Simulation (JASSS)

Received: 29th July 2010 Accepted: 07th January 2011 Published: 31st March 2011

Abstract

The potential of agent-based modeling (ABM) has been demonstrated in various research fields. However, three major concerns limit the full exploitation of ABM; (i) agents are too simple and behave unrealistically without any empirical basis, (ii) "proof of concept" applications are too theoretical and (iii) too much value placed on operational validity instead of conceptual validity. This paper presents an operationalization approach to determine the key system agents, their interaction, decision-making and behavior for context specific ABM, thus addressing the above-mentioned shortcomings. The approach is embedded in the framework of Giddens' structuration theory and the structural agent analysis (SAA). The agents' individual decision-making (i.e. reflected decisions) is operationalized by adapting the analytical hierarchy process (AHP). The approach is supported by empirical system knowledge, allowing us to test empirically the presumed decision-making and behavioral assumptions. The output is an array of sample agents with realistic (i.e. empirically quantified) decision-making and behavior. Results from a Swiss mineral construction material case study illustrate the information which can be derived by applying the proposed approach and demonstrate its practicability for context specific agent-based model development.

Keywords:
Agent-based modeling (ABM), agent operationalization, decision-making, analytical hierarchy process (AHP), conceptual validation

1 Introduction

During the last decade, agent-based modeling (ABM) has been regarded as a promising methodology for quantitative modeling in the social sciences (Axelrod 1997; Epstein and Axtell 1996; Gilbert and Troitzsch 2005; Janssen 2002; Tesfatsion and Judd 2006), but not without contradictory trends. Although ABM's potential for modeling a variety of phenomena in different research fields has been repeatedly demonstrated (e.g. (Bousquet and Le Page 2004; Macy and Willer 2002)), its effectiveness in solving problems more relevant to the real world is increasingly being questioned (Louie and Carley 2008; Parker et al. 2003). The three central questions being raised are: (i) How to go beyond a "proof of concept" (e.g. Janssen and Ostrom (2006)) (ii) How realistic are agents with simple behavioral rules? (e.g. Jager and Janssen (2002), Mosler and Tobias (2005)) (iii) How could or should agent-based models be validated? (e.g. Axelrod (1997), Windrum et al. (2007), Louis and Carley (2008)).

During the last decade, agent-based modeling (ABM) has been regarded as a promising methodology for quantitative modeling in the social sciences (Axelrod 1997; Epstein and Axtell 1996; Gilbert and Troitzsch 2005; Janssen 2002; Tesfatsion and Judd 2006), but not without contradictory trends. Although ABM's potential for modeling a variety of phenomena in different research fields has been repeatedly demonstrated (e.g. (Bousquet and Le Page 2004; Macy and Willer 2002)), its effectiveness in solving problems more relevant to the real world is increasingly being questioned (Louie and Carley 2008; Parker et al. 2003). The three central questions being raised are: (i) How to go beyond a "proof of concept" (e.g. Janssen and Ostrom (2006)) (ii) How realistic are agents with simple behavioral rules? (e.g. Jager and Janssen (2002), Mosler and Tobias (2005)) (iii) How could or should agent-based models be validated? (e.g. Axelrod (1997), Windrum et al. (2007), Louis and Carley (2008)).

(i) Beyond "proof of concept": While the potential of ABM for addressing a wide range of research question in social sciences is undoubted, there is a growing appreciation that there is a need for addressing problems more relevant to the real world (Matthews et al. 2007). Janssen and Ostrom (2006) claim that ABM has mostly been applied to the modeling of theoretical issues, whereas its application to empirically measurable phenomena is quite rare, and models therefore often do not go beyond a "proof of concept". These authors distinguish four ways (stylized facts, laboratory experiments, role games and case studies) of how empirical data can be included into ABM depending on the number of subjects and the degree of contextualization or generalization. In addition, Boero and Squazzoni (2005) highlight the importance of ABM's empirical embeddedness. They argue that empirical knowledge needs to be integrated into modeling practice and used for micro specification as well as macro validation by integrating ABM with qualitative, quantitative, experimental and participatory methods. Although these studies make a significant contribution to the development and classification of empirically-based ABM, they conclude that new approaches are still needed, in particular regarding the empirical validation of ABM and the formalization of empirical knowledge integration into ABM.

(ii) Behaviorally realistic agents: Most of the recent applications in ABM implement rather simple behavioral rules. The underlying decision-making process, however, is usually not included (Macy and Willer 2002), despite the fact that one of the specific advantages of ABM is its ability to model individual decision-making entities and their interactions (Matthews et al. 2007). This may have two reasons. First, simple behavioral rules are easily implementable, whereas the underlying decision-making is often regarded as a rather complex process (Mintzberg et al. 1976). Second, behavior itself can be better observed than the underlying decision-making processes (Keeney 1982). To overcome these issues, Mosler et al. (2001) highlight the need for a theoretical and empirical (H.-J. Mosler and Tobias 2005) basis for collective action simulation. Following this line, Jager and Janssen (2002) propose a general theoretical decision-making framework, based on the six decision rules applicable to different situations, and propose basing the agent architecture on a solid empirical ground (Janssen 2002). That is, in order to achieve more behaviorally realistic agents, the agents' architecture needs to shift from simple behavioral rules to more complex decision making processes with a solid basis in theory and empiricism.

(iii) Model validation: According to Gilbert and Troitzsch (2005) "a model which can be relied on to reflect the behavior of the target is valid".[3] Operational validation as the most widely accepted way to perform model validation (Sargent 2008) is difficult to perform in ABM (Louie and Carley 2008; Schutte 2010; Windrum et al. 2007). Typically, operational validation is performed by comparing the simulation output with the system (i.e. problem entity, target) data (Gilbert and Troitzsch 2005; Sargent 2008). This is impossible to perform for the future development of a system, and it is rather difficult, if emergent phenomena are modeled. First, per definition, emergent phenomena patterns as aggregated outcomes cannot be predicted by examining the system's elements in isolation (Parker et al. 2003). Second, the empirical detection of emergent phenomena in a real system is difficult, because they are described as patterns rather than as numerical values (Grimm et al. 2005) and are often not recognized. The difficulty with or even impossibility of operational validation for ABM increases the importance of the other ways of model validation, in particular, conceptual model validation. Conceptual model validation is defined as "determining that the theories and assumptions underlying the conceptual model are correct and that the model representation of the problem entity is 'reasonable' for the intended purpose of the model" (Sargent 2008). Consequently, to increase the validity of ABM it is necessary to focus on conceptual model validation rather than on comparing model performance with system data (i.e. operational validation).

Significant contributions in ABM have been made to overcome the three mentioned methodological shortcomings. However, none of them explicitly addresses all three issues. Thus new approaches are still needed to include more behaviorally realistic agents, in

[3] A detailed discussion of the ongoing controversy about verification and validation of simulation models in general is outside the scope of this paper. For further information we refer to e.g. Küppers and Lenhard (2005); Oreskes et al. (1994); Rykiel, (1996); and Sargent (2008).

particular regarding agents' decision-making and behavior, and empirical data, with more emphasis on conceptual validation.

Our paper therefore aims at contributing to filling this gap, by presenting an approach for empirically operationalizing agents, their interaction, decision-making and behavior for ABM. The approach was developed for highly context specific ABM applications where high-stakes and/or reflected decisions are involved. As a participatory approach it requires direct contact with the actors. We exemplify the approach by presenting operationalized agents for an ABM of the Swiss construction stakeholders' material selections case study. In the following we use the term operationalization as "the transformation of an abstract, theoretical concept into something concrete, observable, and measurable" (Scott and Marshall 2005). Furthermore, we define agents as the model representatives of real world social actors, such as construction stakeholders in this case study.

The paper is structured as follows: We start with a short introduction of our case study. Second, we provide an approach for the operationalization of agents' identification, interactions and decision-making for ABM, based on structural agent analysis (SAA) and the analytical hierarchy process (AHP). We support each step of the approach by presenting results from the recycling construction material case study and elaborate the potential and limits of the methods used. Third, we discuss the contribution of the approach to the above mentioned shortcomings. Finally we draw conclusions from our findings and propose further research.

Case study introduction: Demand for recycling mineral construction materials (RMCM) in Switzerland

Increasing amounts of construction and demolition (C&D) waste have been observed worldwide (Bergsdal et al. 2007; Brunner 2004; Hao et al. 2007; Hashimoto et al. 2007; Moser et al. 2004; Muller 2006; Wang et al. 2004). So far, C&D waste has been deposited or reused for low-grade applications (Moser et al. 2004; Tam and Tam 2006). Limited landfill and low-grade application capacities led to the development of high performance applications (e.g. Hoffman and Leemann (2006)). However, due to a lack of construction stakeholders' recycled mineral construction materials (RMCM) acceptance, information and training (Hoffmann 2004; Spoerri et al. 2009), RMCM are still deposited or down-cycled and not reused at the same application level. This study aims at developing strategies for aligning the demand for RMCM and the increasing C&D waste amounts by analyzing and modeling stakeholders' decisions and interaction influencing the demand for RMCM.

2 The agent operationalization approach for ABM

2.1 Conceptual framework for the operationalization approach

Our operationalization approach is based on the conceptual framework presented in Figure 1. The theoretical foundations are Giddens' structuration theory (Giddens 1984) and the theory of planned behavior (Ajzen 1991). Material and energy flows on the aggregate level are affected by micro level agents' decisions and interactions, which in turn are influenced in their decision-making by the social and physical environment (Axtell et al. 2001). This dualism between the micro and macro level (Andrews 2001) relates to key system features modeled with ABM, namely emergence of social structure based on micro behavior and feedback of the new structure on the behavior itself. The structural agent analysis (SAA) uses Giddens' structuration theory (Giddens 1984) for a heuristic aimed at analyzing this micro-macro relationship, more specifically, for coupling social science approaches to material flow analysis (MFA) (Binder 2007b, 2007a). That is, it provides a conceptual basis for the modeling socio-ecological as well as socio-technical systems with ABM.

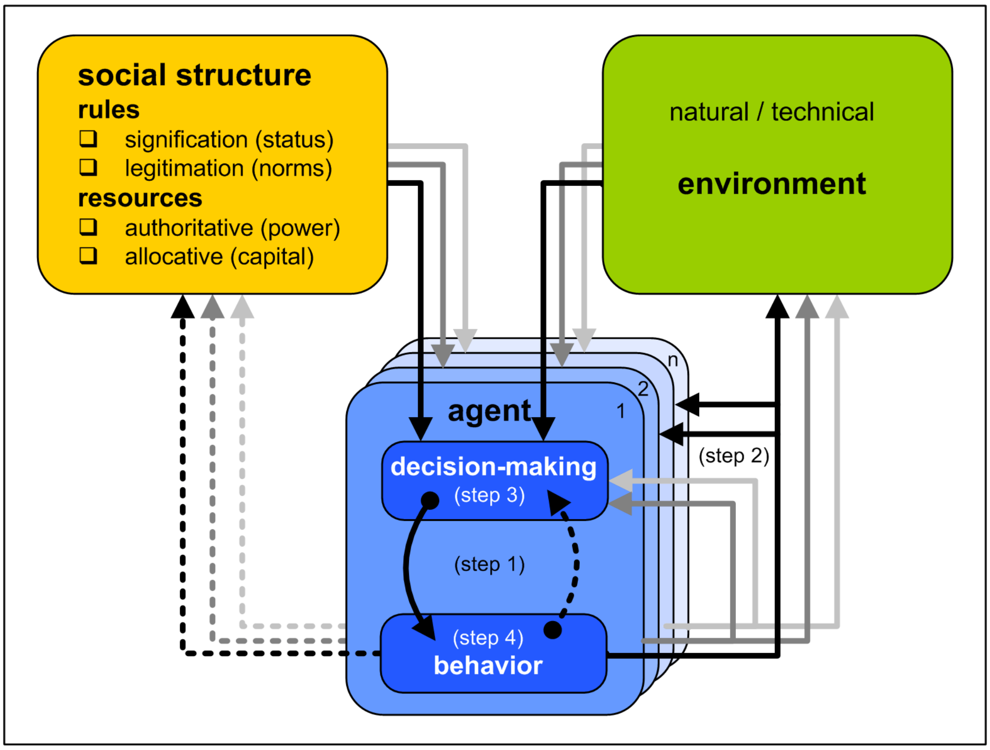

Figure 1: Conceptual framework of the interaction between social structure, agents and the environment (continuous arrows indicate synchronic, dotted arrows indicate diachronic impacts) (adapted from Binder, (2007a), Giddens, (1984) and Nikolic (2009))

This conceptual framework consists of the agents (decision-making and behavior), social structures (rules and resources), and the agents' environment. It includes the consequences of the agents' behavior on social structures, environment (e.g. material flows) and other agents' decisions (Figure 1). The outcome from the decision-making process (i.e. decision preference) can be seen as the intention, according to the theory of planned behavior (Ajzen and Fishbein 1977; Ajzen 1991), determining to a large extent the agents' behavior (Ajzen and Madden 1986). The decision-making itself can be directly affected by past individual behavior and the behavior of other agents, through the perceived intended and unintended consequences (Feola and Binder 2009; Triandis 1980). Furthermore, decision-making can be influenced by the rules and resources of the social structure and the perceived environmental consequences. The behaviors of agents affect the environment synchronically (e.g. the disposal of construction waste that is not reused) and/or the decision-making of other agents (e.g. material recommendations from structural engineers) and with a certain time delay the social structure (e.g. development of law and standards for emergent technologies).

In ABM, system behavior (e.g. social structure and environment) emerges from the agents' behaviors and interactions (Axelrod 1997; Gilbert and Troitzsch 2005; Janssen 2002; Tesfatsion and Judd 2006). Therefore, knowing the relevant agents affecting the problem addressed (step 1), determining their interaction (step 2), analyzing their decision-making process including its determinants (step 3), is sufficient for agent operationalization for ABM (Figure 1). In addition, one must analyze how consistent decision preference (intention) and behavior are (step 4) to conceptually validate the model. For each of the four steps a sound theoretical background and empirical methods are required (Table 1).

Table 1: The four steps of the agent operationalization approach

Step	**Description**	**Theoretical background** (exemplified)	**Methods** (exemplified)
Prerequisite step: Problem definition (Precise definition of the problem addressed and the purpose of the model)			
Step 1	**Identification of the relevant agents**	Social network theory (Wasserman and Faust 1994)	• Agent-impact analysis
Step 2	**Analysis of agents' interaction chain**	Economic action and social structure (Granovetter 1985) and theory of embeddedness (Uzzi 1997)	• Expert interviews • Expert workshops
Step 3	**Quantification of agents' decision-making process**	Multi criteria decision analysis (MCDA) (Belton and Stewart 2002) / Analytical hierarchy process (AHP) (Saaty 1980)	• Expert interviews • Expert workshops • Survey methods
Step 4	**Behavioral consistency analysis and conceptual validation**	Theory of planned behavior (Ajzen 1991) and interpersonal behavior (Triandis 1980)	• Survey methods

In this paper, we use Giddens' structuration theory (Giddens 1984) as a guideline for the assumptions-in-design of the ABM. Giddens' structuration theory is only one among several social process theories (Cedermann 2005) and the issue of how different social process theories could possibly be implemented in ABM and what theory is best suited for each particular model's purposes is still being debated. Nevertheless, the suitability of Giddens' structuration theory for ABM operationalization is highlighted by its focus on how social structure emerges from human action (Binder 2007a). Further, Cedermann (2005) has concluded that the agent-based paradigm is fundamentally compatible with process-theoretical foundations. Finally, because our approach explicitly aims at the agent operationalization, the macro level analysis (i.e. social, technical and natural environment) is not explicitly addressed in this paper.

2.2 Prerequisite step: Problem definition

As a clear purpose and problem definition are considered indispensable for modeling (Costanza et al. 1993), they set the stage for all subsequent steps of the agent operationalization. This is particularly important when one is using participatory approaches for gathering empirical knowledge as is proposed here (Cornwall and Jewkes 1995). Shifting model purposes or problem misunderstandings may otherwise increase the so called "error of the third kind" defined as "the probability of having solved the wrong problem when one should have solved the right problem" (Mitroff and Featheringham 1974).

2.3 Step 1: Identification of the relevant agents

The goal of this step is to identify the key system actors to be included as agents in the ABM. According to social network theory (e.g. Wassermann and Faust (1994)) key system actors within a network are active, able to connect to each other through efficient paths, have the potential to mediate flows between other actors and are tied to other central actors (Faust 1997). In other words, key system actors are actors which strongly affect the system and are themselves strongly affected by the system. In order to identify the key system actors, we propose the actor impact analysis (AIA) adapted from qualitative cross-impact analysis (Godet 1994; Gordon and Hayward 1968; Götze 1991; Scholz and Tietje 2002; Vester 2007; von Reibnitz 1992), which performs an analysis of the actors' activity, revealing their connectedness and impact on other possible actors.

In doing so, first all relevant actors affecting the system are identified. This can be done either by analyzing the actors' interaction with the system along the production-consumption chain (Maier Bergé and Hirsch Hadorn 2002), their functional relationships (Hermans 2005) or by studying which actors interact with each other through, for example, information, money or resource flows (Hirsch Hadorn et al. 2002; Knoeri 2007). The indicator for defining the actor interaction shall be chosen according to the predefined problem definition and model purpose. If multiple indicators are possible several interaction matrixes might be constructed and compared. We propose doing all this by considering literature, expert interviews (H. A. Mieg and Näf 2006) or consensus building expert workshops (Susskind et al. 1999).

Second, all potential direct impacts between the actors are set up in a cross-impact matrix and their strengths are assessed on predefined scales (e.g. from 0 to 2; 0 means no influence, and 2 strong influence). This can be done through expert interviews (Knoeri et al. 2010) or workshops. The sums of the row entries in the matrix reflect the influence values (activity sum) and the sums of the column entries the dependence values (passivity sums) (Godet, 1994, Lang et al., 2006). Thus, depending on their activity or passivity the actors can be classified into disconnected, indicating, driving and key connected actors referring to their roles in the system (Table 2).

Table 2: Actor types in AIA

actor type (role)	**influence value** (activity sum)	**dependence value** (passivity sum)
driving / active	high	low
key connected / ambivalent	high	high
indicating / passive	low	high
disconnected / buffering	low	low

The results of the cross-impact matrix can be visualized in a system grid (Scholz and Tietje 2002; Tietje 2005). Figure 2 illustrates a system grid for the case of RMCM showing the various actor types involved. The key connected actors were the awarding authorities, architects and engineers and contractors (i.e. prime, masonry and concrete, roadwork contractors). They were key in the sense of strongly influencing other actors and being strongly influenced by others. The construction material production actors, deconstruction and disposal actors were passive system actors. They were medium linked with other actors, whereas their strong relations were mainly unidirectional (i.e. they were strongly influenced by other actors). Therefore, they served as indicators for system behavior. In a manner similar to passive actors, active actors (i.e. regulation authorities) had mainly unidirectional relations, although with reversed signs (i.e. they strongly influenced other actors) and acted as drivers in the system. Media (i.e. daily press and journals) as well as academia (research institutes) were considered disconnected or buffering system actors being loosely linked with the system (i.e. fewer and less important relationships). Finally, the key system actors to be included as agents in the model are selected. The ambivalent or key connected actors are considered most important for agent operationalization for ABM, as any change in their behavior has large impacts on the system (Asan and Asan, 2007, Scholz and Tietje, 2002). Consequently the awarding authorities, architects, engineers and contractors were selected for inclusion in the case of RMCM.

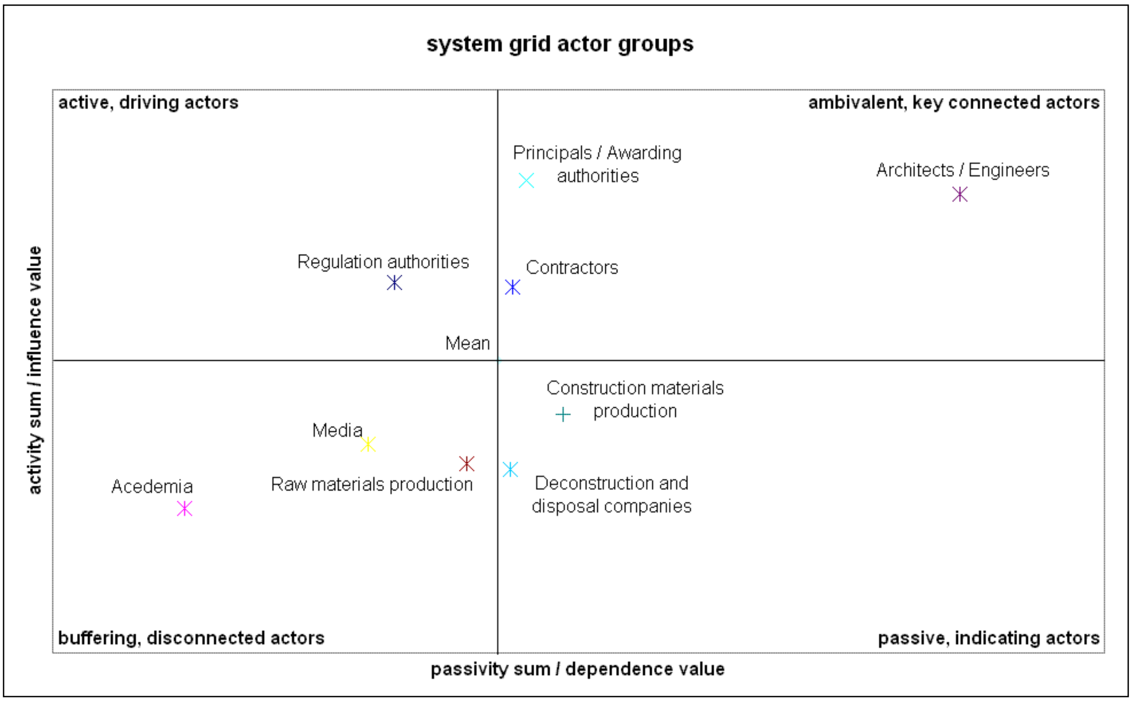

Figure 2: System grid of the actor groups (dependence and influence values; means of the two system experts)

Selecting the key connected actors to be included in ABM ensures that those system actors that are most affected and have the most impact will be included in the model (Faust 1997; Schlange and Juttner 1997; Wasserman and Faust 1994). Nevertheless, other actor groups, especially active actors due to their driving role, may be additionally considered for being operationalized as agents in ABM. However, since these groups are only weakly influenced by the system, they can also be included as external parameters affecting the system. This is the way regulation authorities were included in the RMCM case study, which allows to simulate the effect of regionally-different regulation practices on agents behavior and thus, on the RMCM demand. If the research focus lays on changing regulation practices, regulation authorities might become key connected actors and might be included as agents in the model.

2.4 Step 2: Analysis of agents' interaction chain

This step determines both parts of the agents' interaction: How agents interact with each other (i.e. agents' interaction chain) and how they select each other (i.e. agents' embeddedness). This is considered to be a key step for ABM, because of its focus on agent interaction (Macy and Willer 2002; Reynolds 1987). Furthermore the graph of the agents' interaction chain provides the first conceptual model. Social structure (i.e. agents' interaction chain) and embeddedness in the network (i.e. strength of the ties) are important for agent interaction. It is acknowledged that economic action is embedded in social structure, in contrast to neoclassical atomized-agent approaches (Granovetter 1985). In particular in interfirm networks embeddedness in social structure has beneficial effects on performance (Uzzi 1997). We therefore propose to analyze the agents' local interconnections and embeddedness in two steps.

First, agents' local interconnections and feedbacks (i.e. agents' interaction chain) determining system behavior are identified. In this way we analyze how agents are linked to other agents (e.g. awarding authorities specify project to the architects). This determines which agents potentially interact. Furthermore, possible interaction options (i.e. behavioral alternatives) are identified. We propose doing this step as a combination of literature review and participatory approaches (e.g. expert interviews or workshops) (Cornwall and Jewkes 1995; H. Mieg 2000).

Second, agents' embeddedness in the network or the strength of their ties is analyzed. We propose doing this by analyzing the importance of network factors among the criteria which agents consider when selecting each other for the particular economic interaction (i.e. individual selection decision). According to Ling (2002) this depends on the criteria task performance, contextual performance, network and price factors. Therefore, for each selection decision, the particular decision criteria are defined and their impact is quantified. We suggest defining the criteria with a literature/theory review and weighting their importance on the individual selection decision with survey methods.

Agent interaction chain: Figure 3 shows the conceptual model we have developed for the case of RMCM, illustrating chronologically the agents' interaction chain with multiple involvements of the awarding authorities. In the *project specification (1)* awarding authorities specify the project requirements, dictating the use of RMCM, claiming sustainable construction in general or making no specification about sustainable construction. Receiving the project specifications via the architects, structural engineers make material *design specifications (2)*. They recommend conventional or recycled materials or give the option to choose one of the two, by specifying material properties. Architects *project design (3)* aims at recommending a project to the awarding authorities, meeting awarding authorities' requirements, engineers' recommendations as well as the architects' personal ambitions. In the *project confirmation (4)* the awarding authorities confirm or set the materials to be specified in the tender documents. Contractors submit their *tender (5)* to the awarding authorities in order to win the contract, submitting conventional and recycling materials. Again, awarding authorities commission the project to one of the tendering contractors (i.e. *tender selection (6)*) which finally determines the material demand.

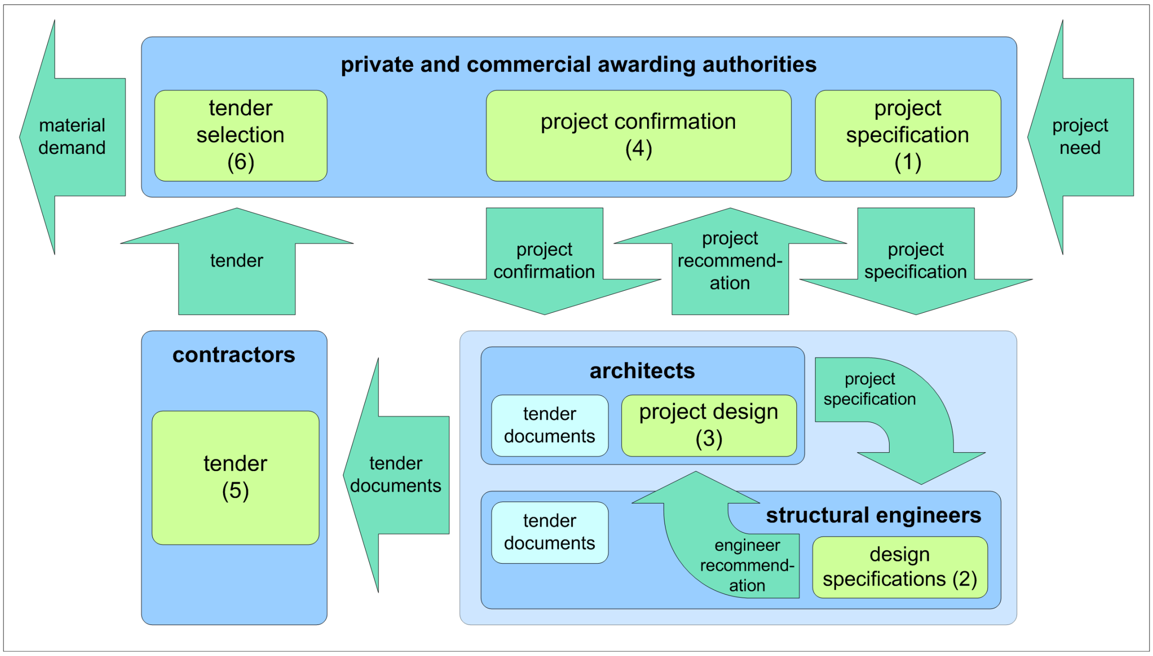

Figure 3: Agent interaction chain (blue boxes indicate the agents, light green boxes their decisions and green arrows their interaction).

The agents' interaction chain is highly context dependent and, therefore, not generalizable to nearby or associated decisions. All the more, there should be a consensus about agents' behavioral options when interacting, which can be achieved through expert interviews and workshops. Note that, for highly formalized interaction models, like those in the case study presented here, concentrating on the interaction decision affecting the problem studied might already be sufficient. For more informal social interaction various additional aspects (e.g. interdependence and relationship aspects) may gain importance (Rusbult and Van Lange, 2003).

Agents' embeddedness / Individual agent selection: According to (Ling 2002), the key criteria for the individual selection decision in the building sector were job experience (task performance factor), reputation and personal contact (network factors) and economic considerations (price factor). Personal contact was the decisive network factor for most agents when selecting construction partners. The exception was public awarding authorities, who basically considered job performance and price factors, and architects who selected contractors mainly based on price considerations.

In the agent operationalization approach, the individual selection decisions were defined on a theoretical (e.g. Ling (2002)) and an empirical basis (e.g. expert interviews), in contrast to many ABM applications where interaction mechanisms are defined on theoretical assumptions only. However, quantifying agents' embeddedness by analyzing how important agents' network criteria are when they select each other for an economic interaction might be limited when criteria have threshold utility functions (e.g. trust) (Uzzi 1997). In this case using hierarchical decision heuristics might be more appropriate. What types of networks emerge from the operationalized selection decisions and how they affect the system output will be addressed in the model evaluation.

The resulting conceptual model of the agents' interaction chain is the first step for ABM. Besides enhancing the understanding of agents' interaction, this approach increases the acceptance of the model through the participatory procedure. For the model implementation, it not only provides the qualitative agent interaction chain but also empirically quantifies the agents' selection decisions reducing the degrees of freedom of the model.

2.5 Step 3: Quantification of the agents' decision-making process

The goal of this step is to quantify the agents' decision-making process. Thus, the decision criteria and their relevance to the choice of one of the behavioral alternatives determined in step 2 are specified.

Decision-making depends on the cognitive effort in the decision-making process (Jager and Janssen 2002; Jungermann et al. 1998; Svenson 1990, 1996) and ranges from simple decision heuristics (requiring little cognitive effort) to homo economicus (a lot of cognitive effort and rational actors). Referring to Svenson (1990, 1996), Jungermann et al. (1998) distinguish routinized, stereotyped, reflected and constructed decisions with increasing cognitive effort involved. Because of the large investment sums involved in strategic economic decisions in general and construction decisions in particular, we propose to quantify reflected decisions according to Svenson (1990, 1996). Thus, decision makers know the options and actively strike a balance among the options regarding different criteria.

Analyzing the relevance of weighted criteria to agents' decision-making is the field of multi criteria decision analysis (MCDA) (Belton and Stewart 2002; Mendoza and Martins 2006). We based our MCDA analysis on the analytical hierarchy process (AHP) proposed by Saaty (1980), because it allowed us to structure complex decision-making processes (Saaty 1990) and to measure ratio scales on all hierarchical levels (Forman and Gass 2001).

Figure 4 illustrates the procedure of the AHP. In the decomposition phase, decision goal and alternatives are defined and the decision problem is decomposed into a hierarchy of decision criteria and sub-criteria clusters. Subsequently, the alternatives are compared with respect to each criterion and sub-criterion, and the relevance of the criteria and sub-criteria is assessed, in comparative judgments on pairs. In the hierarchical composition or synthesis, local criteria and sub-criteria priorities are multiplied to yield an overall alternative ranking. Finally, the consistency of the comparisons of pairs is assessed. (Please see Saaty (1980, 1994) for details and calculations.)

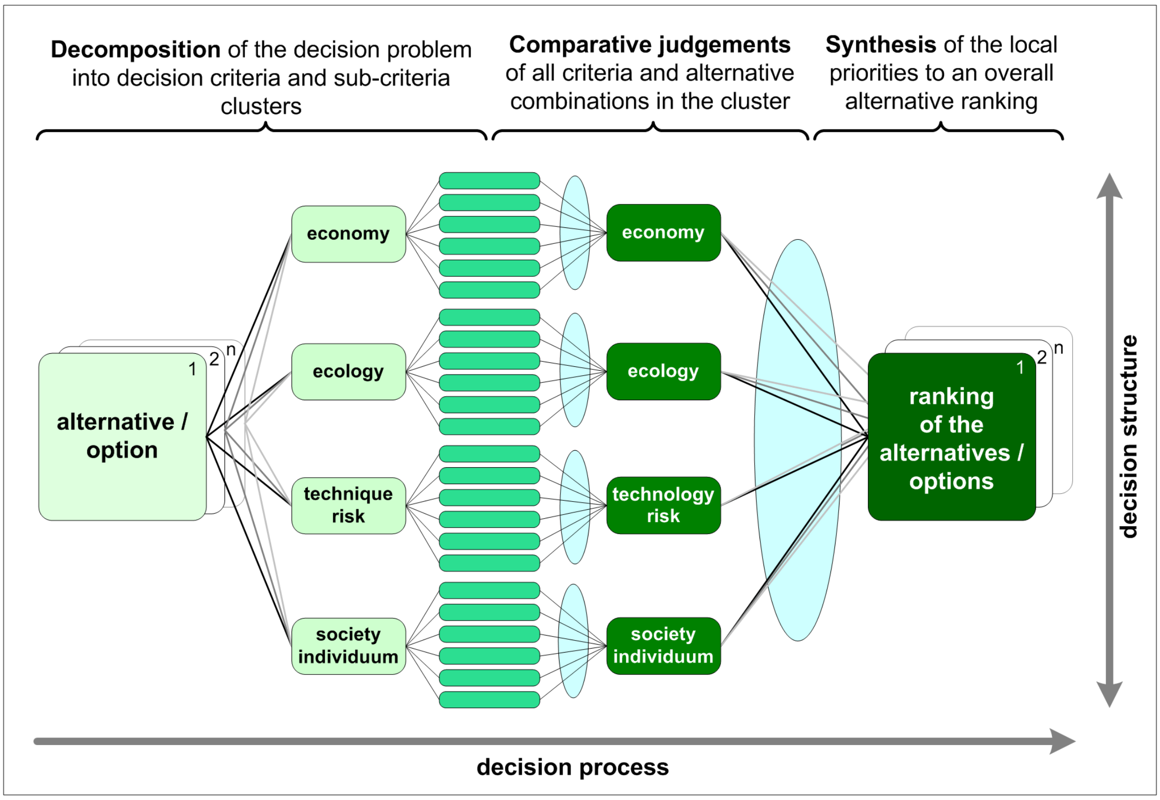

Figure 4: Phases of the analytical hierarchy process according to Saaty (1980, 1994) illustrated with the Brunswikian lens model adapted from Scholz and Tietje (2002).

In the decomposition phase local system knowledge is important. We therefore propose decomposing the decision problem with participatory approaches such as system expert interviews (H. A. Mieg and Näf 2006). We propose using survey methods for quantifying the relevance of criteria and alternatives with comparative judgments. This enables one to achieve a reasonable numerical representation of the agents' decision making distribution in the population. (The AHP elicitation protocol used in the RMCM case study survey is reported in Appendix 1 (Table A.1).) Finally, the synthesis can be carried out through a matrix multiplication of the criteria weight vector with the alternative weight matrix leading to a performance vector of the alternatives (Saaty 1980).

In the RMCM case study each decision of the agent interaction chain (Figure 3) was quantified according to the AHP procedure. Figure 5 shows as an example the decision-making process, criteria and the resulting alternative weights for the design specification decisions of structural engineers (i.e. decision (2) in Figure 3) for external concrete applications in our case study. From the column *Alternative weights per criterion* it can be seen, that the ranking of the alternatives was almost stable among the criteria with conventional concrete (CC) as the outperforming option, although their mean differed significantly. Regarding the expected tender price the three options were more balanced, while for the criterion project specification engineers experienced a performance of CC that was almost three times better than the recycling (RC) or property specification (PS) option. In *Decision criteria weights,* law and standards was the most important criterion followed by experience, whereas expected tender price and awarding authorities' project specification were less important. In addition, the comparably high standard deviations (i.e. up to more than half of the actual value) highlighted the existence of individual agents with different ranking preferences.

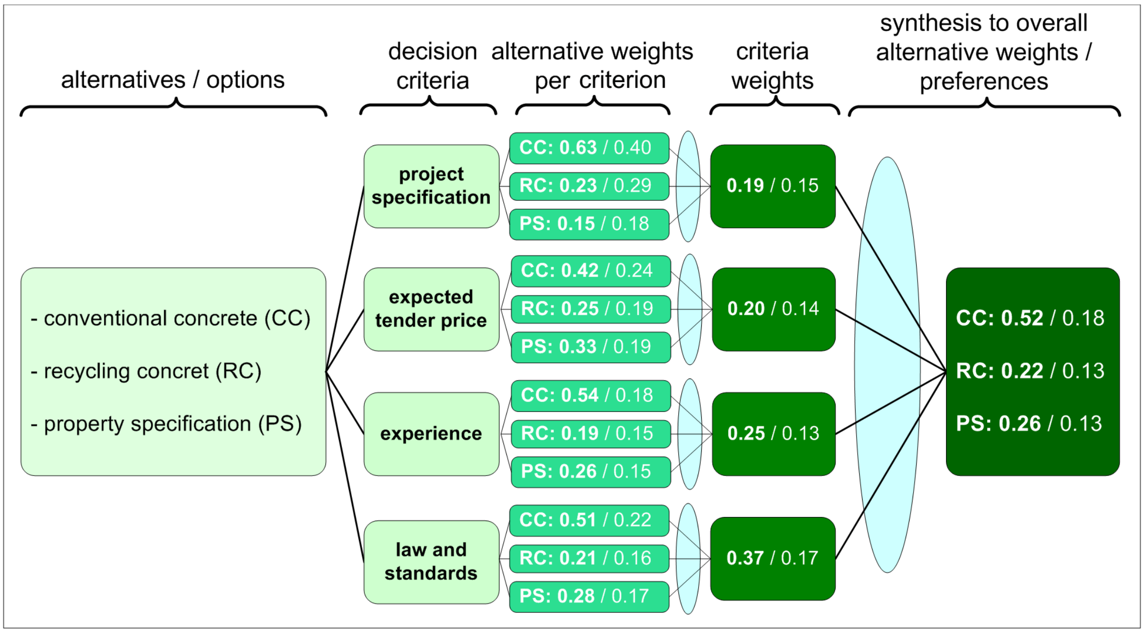

Figure 5: Alternatives, decision criteria, mean alternative weights per criterion, mean criteria weights and mean preferences in structural engineers' design specification for external concrete applications [Mean / StD, N = 70, CC: conventional concrete, RC: recycling concrete: PS: property specification].

AHP as an MCDA approach presupposes that agents fully process their decision information (Mendoza and Martins 2006), decide rationally and don't use simple decision heuristics (Johnson et al. 1988). AHP allows one to do a consistency check of the judgments of pairs, thus providing information on whether the methodical prerequisites are fulfilled. If the decision maker uses simple decision heuristics (e.g. repetition, imitation or normative behavior) MCDA approaches may not be adequate (Johnson et al. 1988; Jungermann et al. 1998; Svenson 1990, 1996). This may limit the applicability of the AHP for decision-making quantification when ordinary and more repetitive decisions are addressed (e.g. everyday consumer behavior). In such cases using other methods for the quantification of agents' decision making or specifying simpler decision rules based on agents behavior might by more adequate. Whenever decision makers decide consciously we consider AHP to be a good starting point, even though the great effort required for making the comparison of pairs in AHP may cause higher rates of survey drop out and lower response compared with behavior reporting studies.

For ABM this quantification procedure has two main advantages. First, it provides not only decision-making data reasonably representing the real population, but it also provides an array of sample agents to set up the model population. This allows one to skip the resource intensive step of deriving mathematical distribution functions from survey data and implementing agent populations based on these distributions. Second, the quantification based on the AHP provides data about all levels of each agent's decision-making process (e.g. criteria and alternative weight matrixes). The procedural structure of AHP further simplifies the decision-making implementation.

2.6 Step 4: Behavioral consistency analysis and conceptual validation

The goal of the last step is to analyze agents' behavioral consistency by comparing their behavior with the preferred alternative from the decision-making process, and to conceptually validate the presumed decision-making concept.

Behavioral consistency: Knowing to what extent the implemented decision-making process or behavioral rule explains actual behavior is fundamental in any behavioral modeling, and particularly in ABM. This is the operational validation of the decision-making model. Although we determined agents' decision-making process (step 3), the preferred alternative (i.e. intention (Ajzen 1991)) may differ from the subsequent behavior, because of external (i.e. contextual factors) and internal drivers (i.e. habit and psychological arousal) (Feola and Binder 2009; Triandis 1980). In addition, perceived behavioral control may influence behavior directly and via intention (Ajzen, 1991, Armitage and Conner, 2001). Assuming rational stakeholders, the best performing alternative, derived by the AHP synthesis (Figure 4), is preferred. Comparing the best performing alternative for every individual agent with his actual behavior allows one to assess whether the intended behavior (i.e. decision preference) differs from the reported one. We propose determining the behavior of the key agent groups with survey methods (e.g. according to Diekmann (2007)) in combination with the survey conducted for analyzing the decision-making process (Step 3). In the case of RMCM, structural engineers' preferred option was highly consistent (77%) with reported behavior. They decided for the conventional alternative (i.e. best performing) in 80% of the structural concrete application cases (60% for lean concrete applications).

The high behavioral consistency confirmed that in reflected decisions the effect of perceived behavioral control (Armitage and Conner 2001) as well as the effect of habit and psychological arousal is minimized. Although the high behavioral consistency demonstrates the usefulness of the decision-making model, potential differences between actual and reported behavior may limit the usefulness of our approach. This is because of more frequently reported socially desirable answers or biases in survey participation. This difference can be quantified and the limitations minimized by analyzing how the sample represents the basic population studied regarding socio-demographic and behavioral variables.

Conceptual validation: Conceptual validation requires assuring that theories and assumptions underlying the decision-making model are correct. This goes beyond providing a decision-making model simply mirroring behavior. According to Svenson (1990, 1996), the assumption behind quantifying decision-making with AHP is a reflected decision, where decision-makers consciously strike a balance between known alternatives and decision criteria. In reflected decisions we expect to derive consistent judgments in the AHP comparisons of pairs. In other words, comparing options of pairs reveals absolute options' values, which mirror the relative judgments. The AHP consistency analysis gives insight into how consistently the comparisons were made and therefore how high the cognitive effort in the decision was. A certain inconsistency (10%) is hereby accepted in the standard AHP (Saaty 1980). In the adapted procedure presented here, alternatives and criteria were predefined and therefore higher inconsistencies were expected. In the case of RMCM, structural engineers showed slightly higher inconsistencies (i.e. 44% for weighting the criteria, 24% for weighting alternatives) in their comparative judgments compared with the other agent groups. In other words, they may use simpler decision heuristics.

The steps of comparing decision-making preferences and behavior as well as empirically validating underlying decision-making assumptions are key for ABM. Analyzing behavioral consistency allows one to assess the operational validity of the decision-making model. The conceptual validity of the decision-making process further increases the overall conceptual validity of the ABM.

3 Discussion

This paper addressed three major shortcomings limiting a full exploitation of ABM's potential; (i) applications "proof of concept" that is too theoretical, (ii) agents that are too simple and not behaviorally realistic and lack a basis on empirical data and (iii) too much value placed on operational validity instead of conceptual validity. Furthermore, the agent operationalization approach was presented as a specific procedure that links theoretical concepts and empirical methods addressing the above mentioned shortcomings. This approach provides guidance to identify the relevant agents, analyze their interaction, quantify their decision-making and conceptually validate agents' decision-making. In the following we discuss how the agent operationalization approach contributes to each of the shortcomings highlighted in the introduction.

3.1 Beyond proof of concept

Janssen and Ostrom (2006) argue that "although most models are inspired by observations of real biological and social systems, many of them have not been rigorously tested using empirical data and therefore do not go beyond a 'proof of concept'." Including empirical system knowledge regarding ABM is referred to as participatory or collaborative modeling (Voinov and Bousquet 2010). According to Moss (2008), the agent operationalization approach lies between the "economic modeling" and the "companion modeling" approach. Like the economic modelers we presume the existence of a real data generating process (e.g. decision-making process) (Windrum et al. 2007), but we aim at observing and quantifying it directly by including local system knowledge as in the companion modeling approach (Barreteau 2003; Bousquet and Le Page 2004). Integrating empirical system knowledge has been found to be important for case studies in general (Scholz and Tietje 2002) and resource management in particular (Pahl-Wostl 2007). Furthermore it generates trust in the model through participant identification (Berger et al. 2007) and promotes ownership through stakeholder involvement (Nikolic 2009).

The contribution of the here presented agent operationalization approach consists in providing a specific strategy for embedding empirical knowledge into modeling practice as called for by Boero and Squazzoni (2005). Therefore, empirical knowledge is gathered at each step of the approach. However, the proposed approach to operationalizing agents for ABM was developed as a case-based model. The price for higher model realism achieved by this context dependency is less generality (Costanza et al. 1993). We acknowledge the broad range of ABM application from highly context specific “case-based models” to generalizable “theoretical abstractions”, influencing the type of empirical data and validation methods required (Boero and Squazzoni 2005; Janssen and Ostrom 2006). The adaptation of the proposed approach for operationalizing agents to “typifications” or “theoretical abstractions” will therefore be the subject for further research.

3.2 Behaviorally realistic agents

Focusing on individual decision-making rather than on simple behavioral rules (Macy and Willer 2002) is the first step required towards more behaviorally realistic agents (Janssen 2002). The agent operationalization approach contributes to that by obtaining an array of sample agents (including their decision-making and behavior) as well as allowing one to operationally validate the individual decision-making model by comparing decision-making preferences and behavior (i.e. behavioral consistencies):

Array of sample agents: The array of sample agents is obtained by operationalizing the agents’ decision-making process through the AHP. AHP allows one to indirectly gather data about agents decisions by weighting criteria and alternatives per criterion, while the final alternative decision is derived by a simple matrix calculation (Saaty 1990). The ratio-scale weighting method we have included (Jia et al. 1998) simplifies transfer of the derived information into ABM. In other words, deriving an array of sample agents’ decision-making based on AHP provides not only a set of directly implementable decision-making data but also the procedure for its processing. This significantly reduces the models’ degree of freedom and decreases the parameters space to scan. However, there will still be remaining assumptions-in-design which have to be specified (e.g. agents’ time horizon for their retrospective memory) and whose effects on the system output have to be analyzed.

Behavioral consistencies: Decision preferences (i.e. intention) and their consistency with real behavior are central parameters for operationalizing more behaviorally realistic agents for ABM. Comparing a decision-making outcome with actual behavior allows one to assess how well a particular decision-making model mirrors behavior. A further advantage of the combined quantification of decision-making and behavior for ABM agent operationalization is that simple decision heuristics (e.g. based on socio-demographic variables and behavior) can be implemented instead of the complex AHP decision-making process, whenever operational validation fails.

3.3 Conceptual validation

We have argued that "ensuring that the theories and assumptions underlying the conceptual model are correct" (i.e. conceptual validation) should be given more importance in the validation process of ABM, instead of concentrating on operational validation. The need for a "micro-level validation" (i.e. ensuring that micro-level behavior adequately represents actors' activity (Gilbert 2004)) in order to reproduce human-like behavior and thinking, is highlighted by Takadama et al. (2008). The agent operationalization approach contributes to that by providing a specific procedure with which to assess the conceptual validity of the models.

Each step of the agent operationalization approach - from the selection of the agents to the inclusion to their individual decision-making and behavior - draws upon local system knowledge, either qualitatively through expert interviews or quantitatively through surveys. This allows us to test the assumptions made in each step of the model development procedure leading to the conceptual model and, therefore, to ensure the validity of the conceptual model (Sargent 2008).

However, the approach was developed for a contextual, case-based model purpose. Validation may have different meanings for different model purposes (Küppers and Lenhard 2005) which is why different validation techniques and procedures exist (Louie and Carley 2008; Moss 2008). Even though in our approach the focus is on conceptual validation, we acknowledge the importance of verification (e.g. computerized model validation) and operational validation for ABM development and validation (Louie and Carley 2008; Sargent 2008; Takadama et al. 2008). Louie and Carley (2008) have proposed a framework for how models ought to be validated based on their purpose. However, how to exactly balance verification, conceptual and operational validation depending on the model purpose is still an open question.

4 Conclusion

This paper presented an agent operationalization approach, with the aim of providing a comprehensive framework to operationalize key system agents, their interaction, decision-making and behavior for ABM, exemplified by means of the Swiss mineral construction material case study.

The approach addresses three major concerns limiting ABMs' full potential:

(i) Going beyond a "proof of concept": The approach gives a specific strategy for embedding empirical knowledge into modeling practices. It provides a step-by-step procedure for identifying the relevant agents to be included in the ABM and for analyzing their interaction chain in participatory approaches (e.g. expert interviews and workshops), thus enhancing the credibility of models implemented consequently.

(ii) Behaviorally realistic agents: The approach provides an array of sample agents with realistic (i.e. empirically quantified) decision-making and behavior, reducing the parameter space to scan. Quantifying agents' decisions with AHP provides not only a set of directly implementable decision-making data but also an opportunity to test decision-making assumptions empirically. In addition, checking the consistency of the decision-making outcome with behavior allows one to further validate/falsify the implemented decision-making theory.

(iii) Conceptual validity: The approach enhances the importance of conceptual model validity by providing a way to empirically test one's theoretical assumptions.

The comprehensive framework embedded in social process theory and decision making theory leads to more behavioral realistic agents and increases the conceptual model validity. The credibility of ABM is increased by the use of participatory processes. The example of the Swiss construction material case has demonstrated the practicability of the approach. The approach thus provides a transparent and well founded procedure applicable to a broad field of socio-ecological and socio-technical system modeling problems with ABM to the degree possible within the limits of the constituent theory and method. Further research should deal with, highlighting the added value of the approach by modeling the agents' interaction and adapting the approach for more generalizable ABM applications and cases with more informal social interaction and less cognizant decisions.

Acknowledgements: The authors thank all the experts for their support, time and knowledge; the three anonymous reviewers, Giuseppe Feola and Bernhard Steubing for their valuable comments; Thomas Ruddy and Andrea Delduce for editing the text; and FEDRO (Swiss Federal Roads Office), FOEN (Federal Office for the Environment), AWEL (Amt für Abfall, Wasser, Energie und Luft; Environmental Agency) of the Canton of Zurich, AHB (Amt für Hochbauten; Office for structural engineering) of the City of Zurich and Eberhard Recycling AG for funding the study as part of a cooperative project with the TSL (Technology and Society Laboratory) at EMPA and the SIE (Social and Industrial Ecology) group at University of Zurich.

References

Ajzen, I. (1991), 'The theory of planned behavior', *Organizational Behavior and Human Decision Processes,* 50 (2), 179-211.

Ajzen, I. and Fishbein, M. (1977), 'Attitude-behaviour relations - theoretical analysis and review of empirical research', *Psychological Bulletin,* 84 (5), 888-918.

Ajzen, I. and Madden, T. J. (1986), 'Prediction of goal-directed behavior - attitudes, intentions, and perceived behavioral-control', *Journal of Experimental Social Psychology,* 22 (5), 453-74.

Armitage, C. J. and Conner, M. (2001), 'Efficacy of the theory of planned behaviour: A meta-analytic review', *British Journal of Social Psychology,* 40, 471-99.

Axelrod, R. (1997), *The complexity of cooperation: Agent-based models of competition and collaboration* (Princeton: Princeton University Press).

Barreteau, O. (2003), 'Our companion modelling approach', *Journal of Artificial Societies and Social Simulation,* 6 (2).

Belton, V. and Stewart, T. S. (2002), *Multi criteria decision analysis. An integrated approach* (Boston: Kluwer Academic Press).

Berger, T., et al. (2007), 'Capturing the complexity of water uses and water users within a multi-agent framework', *Water Resources Management,* 21 (1), 129-48.

Bergsdal, H., et al. (2007), 'Dynamic material flow analysis for Norway's dwelling stock', *Building Research and Information,* 35 (5), 557-70.

Binder, C.R. (2007a), 'From material flow analysis to material flow management Part II: The role of structural agent analysis', *Journal of Cleaner Production,* 15, 1605-17.
Binder, C.R. (2007b), 'From material flow analysis to material flow management Part I: social sciences modeling approaches coupled to MFA', *Journal of Cleaner Production,* 15 (17), 1596-604.
Boero, Riccardo and Squazzoni, Flaminio (2005), 'Does Empirical Embeddedness Matter? Methodological Issues on Agent-Based Models for Analytical Social Science', *Journal of Artificial Societies and Social Simulation,* 8 (4), 1460-7425.
Bousquet, F. and Le Page, C. (2004), 'Multi-agent simulations and ecosystem management: a review', *Ecological Modelling,* 176, 313-32.
Brunner, P.H (2004), 'Material flow analysis and the ultimate sink', *Journal of Industrial Ecology,* 8 (3), 4-7.
Cedermann, Lars-Eric (2005), 'Computational models of social forms; advancing generative process theory', *American Journal of Sociology,* 110 (4), 864-93.
Cornwall, A. and Jewkes, R. (1995), 'What is participatory research?', *Social Science & Medicine,* 41 (12), 1667-76.
Costanza, R., et al. (1993), 'Modeling complex ecological economic-systems - toward an evolutionary, dynamic understanding of people and nature', *Bioscience,* 43 (8), 545-55.
Diekmann, A. (2007), *Empirische Sozialforschung; Grundlagen, Methoden, Anwendungen [Empirical social research. foundations, methods, applications]* (17; Reinbek: Rowohlt).
Epstein, Joshua M. and Axtell, Robert (1996), *Growing artificial societies: social science from the bottom up* (Washington, D.C: Brookings Institution Press).
Faust, K. (1997), 'Centrality in affiliation networks', *Social Networks,* 19 (2), 157-91.
Feola, G. and Binder, C. (2009), 'The integrative agent-centered (IAC) framework as a conceptual tool to investigate transition processes in local agricultural systems.', *First European Conference on Sustainability Transitions: Dynamics and Governance of Transitions to to Sustainability* (Amsterdam, The Netherlands).
Forman, E. H. and Gass, S. I. (2001), 'The analytic hierarchy process - an exposition', *Operations Research,* 49 (4), 469-86.
Giddens, A. (1984), *The constitution of the society* (Berkeley, CA: University of California Press).
Gilbert, N. (2004), 'Open problems in using agent-based models in industrial and labor dynamics', in Roberto Leombruni and M. Richardi (eds.), *Industry and Labor Dynamics: the agent-based computational approach* (World Scientific), 401-05.
Gilbert, N. and Troitzsch, K. G. (2005), *Simulation for the social scientist.* (2 edn.; Berkshire, England: Open University Press, McGraw-Hill).
Godet, M. (1994), *From Anticipation to Action: A Handbook of Strategic Prospective* (Paris: UNESCO).
Gordon, T. J. and Hayward, H. (1968), 'Initial experiments with cross impact matrix method of forecasting ', *Futures,* 1 (2), 100-16.
Götze, U. (1991), *Szenario-Technik in der strategischen Unternehmungsplanung [Scenorio-method in strategic corporate planning]* (Wiesbaden: Deutscher Universitätsverlag).
Granovetter, M. (1985), 'ECONOMIC-ACTION AND SOCIAL-STRUCTURE - THE PROBLEM OF EMBEDDEDNESS', *American Journal of Sociology,* 91 (3), 481-510.
Grimm, V., et al. (2005), 'Pattern-oriented modeling of agent-based complex systems: Lessons from ecology', *Science,* 310 (5750), 987-91.
Hao, J.L., Hills, M.J., and Huang, T. (2007), 'A simulation model using system dynamic method for construction and demolition waste management in Hong Kong', *Construction Innovation,* 7 (1), 7-21.
Hashimoto, Seiji , Tanikawa, Hiroki , and Moriguchi, Yuichi (2007), 'Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan', *Waste Management,* 27, 1725-38.

Hermans, L. M. (2005), 'Dynamic actor network analysis for diffuse pollution in the province of North-Holland', *Water Science and Technology,* 49 (2), 205-12.

Hirsch Hadorn, G. , Wölfling Kast, S., and Maier, S. (2002), 'Restrictions and options: A heuristic tool to integrate knowledge for strategies towards a sustainable development.', *International Journal of Sustainable Development and World Ecology,* 18 (9), 193-207.

Hoffmann, Cathleen (2004), 'Materialkenngrößen von Beton aus Mischabbruch [Material properties of recycling concrete with mixed rubble aggregates]', (Zürich: Amt für Hochbauten der Stadt Zürich, Material Science and Technology (EMPA)), 37.

Hoffmann, Cathleen and Leemann, Andreas (2006), 'Recycled concrete and mixed rubble as aggregates: Influence of variations in composition on the concrete properties', *Advances in Cement and Concrete X: Sustainability* (Davos, Switzerland), 211-15.

Jager, W. and Janssen, M. (2002), 'The need for and development of behaviourally realistic agents', in J. S. Sichman, F. Bousquet, and P. Davidsson (eds.), *3rd International Workshop on Multi-Agent-Based Simulation II (MABS 2002)* (Bologna, Italy: Springer-Verlag Berlin), 36-49.

Janssen, M. A. (2002), *Complexity and ecosystem management: the theory and practice of multi-agent systems* (Cheltenham: Elgar).

Janssen, M. A. and Ostrom, E. (2006), 'Empirically based, agent-based models', *Ecology and Society,* 11 (2).

Jia, J., Fischer, G. W., and Dyer, J. S. (1998), 'Attribute weighting methods and decision quality in the presence of response error: A simulation study', *Journal of Behavioral Decision Making,* 11 (2), 85-105.

Johnson, E. J., Payne, J. W., and Bettman, J. R. (1988), 'Information displays and preference reversals', *Organizational Behavior and Human Decision Processes,* 42 (1), 1-21.

Jungermann, Helmut , Pfister, Hans-Rüdiger , and Fischer, Katrin (1998), *Die Psychologie der Entscheidung: eine Einführung [Decision psychology - an introduction]* (Spektrum Lehrbuch; Heidelberg: Spektrum Akademischer Verlag).

Keeney, R. L. (1982), 'Decision-analysis - an overview', *Operations Research,* 30 (5), 803-38.

Knoeri, C. (2007), 'Agent based modeling (ABM) for analyzing demand for recycled mineral construction material ', Diploma Thesis (Swiss Federal Institute of Technology ETH).

Knoeri, C., Binder, C. R., and Althaus, H.J. (2010), 'Decisions on recycling: construction stakeholders' decisions regarding recycled mineral construction materials', *Resources, Conservation and Recycling*.

Küppers, G. and Lenhard, J. (2005), 'Validation of Simulation: Pattern in the social and Natural Science', *Journal of Artificial Societies and Social Simulation,* 8 (4).

Ling, Y. Y. (2002), 'A conceptual model for selection of architects by project managers in Singapore', *International Journal of Project Management,* 21 (2003), 135-44.

Louie, M. A. and Carley, K. M. (2008), 'Balancing the criticisms: Validating multi-agent models of social systems', *Simulation Modelling Practice and Theory,* 16 (2), 242-56.

Macy, M. W. and Willer, R. (2002), 'From factors to actors: Computational sociology and agent-based modeling', *Annual Review of Sociology,* 28, 143-66.

Maier Bergé, S. and Hirsch Hadorn, G. (2002), 'Options & Restrictions: A heuristic tool in transdiciplinary research for an effective implementation of sustainable practices', in F. Biermann, S. Campe, and Jacob K. (eds.), *2002 Berlin Conference on the Human Dimensions of Global Environmental Change „Knowledge for the Sustainability Transition. The Challenge for Social Science" Global Governance Project* (19; Amsterdam, Berlin, Potsdam (Germany) and Oldenburg (Germany)), 322-36.

Matthews, R. B., et al. (2007), 'Agent-based land-use models: a review of applications', *Landscape Ecology,* 22 (10), 1447-59.

Mendoza, G. A. and Martins, H. (2006), 'Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms', *Forest Ecology and Management,* 230 (1-3), 1-22.

Mieg, HA. (2000), 'University-based projects for local sustainable development: Designing expert roles and collective reasoning', *International Journal of Sustainability in Higher Education* 1, 67-82.
Mieg, Harald A. and Näf, Matthias (2006), *Experteninterviews in den Umwelt- und Planungswissenschaften [Expert interviews in environmental and management research]* (Lengerich: Pabst Science Publishers).
Mintzberg, H., Raisinghani, D., and Theoret, A. (1976), 'Structure of unstructured decision-processes', *Administrative Science Quarterly,* 21 (2), 246-75.
Mitroff, II and Featheringham, T. R. (1974), 'Systemic Problem-Solving and Error of 3rd Kind', *Behavioral Science,* 19 (6), 383-93.
Moser, K., et al. (2004), 'Baustoffmanagement 21 an der EMPA, Stand des Wissens und Forschungsbedarf [Management of construction materials at EMPA: standard of knowledge and need for further research]', (Material Science and Technology (EMPA)).
Mosler, H.-J. and Tobias, R. (2005), 'Simulation of collective action based on empirical data', *2nd International Conference of the European Social Simulation Association* (Valladolid, Spain).
Mosler, H. J., et al. (2001), 'Computer simulation as a method of further developing a theory: Simulating the elaboration likelihood model', *Personality and Social Psychology Review,* 5 (3), 201-15.
Moss, S. (2008), 'Alternative Approaches to the Empirical Validation of Agent-Based Models', *Journal of Artificial Societies and Social Simulation,* 11 (15).
Muller, D. B. (2006), 'Stock dynamics for forecasting material flows - Case study for housing in The Netherlands', *Ecological Economics,* 59 (1), 142-56.
Nikolic, Igor (2009), *Co-evolutionary method for modelling large scale socio-technical systems evolution* (Delft, The Netherlands: Next Generation Infrastructures Foundation).
Oreskes, Naomi, Shrader-Frechette, Kristin, and Belitz, Kenneth (1994), 'Verification, validation and confirmation of numerical models in the earth sciences', *Science,* 263 (5147), 641-46.
Pahl-Wostl, C. (2007), 'The implications of complexity for integrated resources management', *Environmental Modelling & Software,* 22 (5), 561-69.
Parker, C., et al. (2003), 'Multi-agent systems for the simulation of land-use and land-cover change; a review', *Annals of the Association of American Geographers,* 93 (2), 314-37.
Reynolds, C. W. (1987), 'Flocks, herds, and schools: a distributed behavioral model', *Computer Graphics (SIGGRAPH '87 Conference Proceedings),* 21 (4), 25-34.
Rykiel, E. J. (1996), 'Testing ecological models: The meaning of validation', *Ecological Modelling,* 90 (3), 229-44.
Saaty, T. L. (1980), *The analytical hierarchy process: planning, priority setting, resource allocation* (New York: McGraw-Hill).
Saaty, T. L. (1990), 'How to Make a Decision - the Analytic Hierarchy Process', *European Journal of Operational Research,* 48 (1), 9-26.
Saaty, T. L. (1994), *Fundamentals of decision making* (Pittsburgh, PA: RWS Publication).
Sargent, R. G. (2008), 'Verification and validation of simulation models', *2008 Winter Simulation Conference* (Washington, DC), 112-25.
Schlange, L. E. and Juttner, U. (1997), 'Helping managers to identify the key strategic issues', *Long Range Planning,* 30 (5), 777-86.
Scholz, R.W. and Tietje, O. (2002), *Embedded case study methods; Integrating quantitative and qualitative knowledge* (Thousand Oaks: Sage Publications).
Schutte, Sebastian (2010), 'Optimization and Falsification in Empirical Agent-Based Models', *Journal of Artificial Societies and Social Simulation,* 13 (1), 2.
Scott, John and Marshall, Gordon (2010), '"operational definition."', *Oxford Dictionary of Sociology* (updated 2006) www.enotes.com/oxsoc-encyclopedia/operational-definition , accessed 5 May.

Spoerri, Andy, et al. (2009), 'Expert-based scenarios for strategic waste and resource management planning - C&D waste recycling in the Canton of Zurich, Switzerland', *Resources, Conservation and Recycling,* 53 (10), 592-600.

Susskind, L., McKearnnan, S., and Thomas-Larmer, J. (1999), *The consensus building handbook - a comprehensive guide to reach agreement* (Thousand Oaks, CA: Sage).

Svenson, O. (1990), *SOME PROPOSITIONS FOR THE CLASSIFICATION OF DECISION SITUATIONS*, eds K. Borcherding, O. I. Larichev, and D. M. Messick (Contemporary Issues in Decision Making; Amsterdam: Elsevier Science Publ B V) 17-31.

Svenson, O. (1996), 'Decision making and the search for fundamental psychological regularities: What can be learned from a process perspective?', *Organizational Behavior and Human Decision Processes,* 65 (3), 252-67.

Takadama, K. , Kawai, T , and Koyama, Y (2008), 'Micro- and Macro-Level Validation in Agent-Based Simulation: Reproduction of Human-Like Behaviors and Thinking in a Sequential Bargaining Game', *Journal of Artificial Societies and Social Simulation,* 11 (2).

Tam, V. W. and Tam, C. M. (2006), 'A review on the viable technology for construction waste recycling', *Resources Conservation and Recycling,* 47 (3), 209-21.

Tesfatsion, L. and Judd, K. L. (2006), *Handbook of computational economics: agent-based computational economics* (Handbooks in economics, 2; Amsterdam: Elsevier).

Tietje, O. (2005), 'Identification of a small reliable and efficient set of consistent scenarios', *European Journal of Operational Research,* 162 (2), 418-32.

Triandis, H.C. (1980), *Values, Attitudes and Interpersonal Behaviour, Nebraska Symposium on Motivation* (Lincoln/London: University of Nebraska Press).

Uzzi, B. (1997), 'Social structure and competition in interfirm networks: The paradox of embeddedness', *Administrative Science Quarterly,* 42 (1), 35-67.

Vester, F. (2007), *The art of interconnected thinking: Tools and concepts for a new approach to tackling complexity* (Munich, Germany: MCB).

Voinov, Alexey and Bousquet, Francois (2010), 'Modelling with stakeholders', *Environmental Modelling & Software,* 25 (11), 1268-81.

von Reibnitz, U. (1992), *Szenario-Technik. Instrumente für die unternehmerische und persönliche Erfolgsplanung [Scenario-methods; Instruments for corporate and personal planning]* (Wiesbaden, Germany: Gabler).

Wang, J. Y., et al. (2004), 'A systems analysis tool for construction and demolition wastes management', *Waste Management,* 24 (10), 989-97.

Wasserman, S. and Faust, K. (1994), *Social Network Analysis: Methods and Applications* (Cambridge Univ. Press).

Windrum, P., Fagiolo, G., and Moneta, A. (2007), 'Empirical Validation of Agent-Based Models: Alternatives and Prospects', *Journal of Artificial Societies and Social Simulation,* 10 (2).

Appendix 1: Questionnaire AHP elicitation protocol

Table A.1: AHP elicitation protocol in the questionnaire exemplified by the structural engineers' design specification decision

Questions to the material choice:	
In the project specification phase, you decided which materials you advised the architects to specify in the tender documents for which application. In this decision the following three options were possible.	
1: Specify conventional materials	You advised the architect to specify and use conventional materials
2. Specify recycled mineral construction materials (RMCM)	You advised the architect to specify and use recycled mineral construction materials (RMCM)
3. Property specification	You advised the architect to specify the required material properties in the tender documents. This way, conventional materials or RMCM or the two as alternatives could be offered.
The following criteria were generally considered important for engineers when they specify what materials to use, as first results from an expert workshop showed.	
Project specification	**The project specification for the awarding authorities** regarding sustainable construction in general and/or the use of RMCM.
Expected tender price	**The expected tender price** of conventional materials or RMCM.
Experience	Your **experience** with conventional materials and RMCM.
Law and standards	How **law and standards** favor the use of conventional materials or RMCM.
It is supposable that your decision differs depending on the application and the type of RMCM to be used. Therefore, we consider the following three different applications.	
A. **Structural concrete for wet outdoor applications** (concrete slab, walls) B. **Structural concrete for dry indoor applications** (concrete slab, walls, ceilings) C. **Lean concrete applications** (Blinding layer, back fillings)	
For each of this three applications conventional materials and RMCM will be compared. The following material options will be considered.	
Conventional concrete	Conventional concrete with primary material aggregates (gravel/sand)
Recycling concrete B:	RC-Concrete B; (25-100%) concrete rubble aggregates (crushed rubble from concrete building elements)
Recycling concrete M:	RC-Concrete M; (25-100%) mixed rubble aggregates (crushed mixed rubble from clinker, lime-sand and natural brick works and from concrete building elements)
In following we ask you to define the criteria weights and to evaluate the material options regarding each criterion for each of the three applications.	

Please answer the questions for the following application:										
A Structural concrete for wet outdoor applications										
How important were the following criteria in comparison when you recommended materials for wet outdoor structural concrete applications?										
Criterion A	Criterion A dominant	Very strongly more important	Strongly more important	Slightly more important	Equally important	Slightly more important	Strongly more important	Very strongly more important	Criterion B dominant	Criterion B
Project specification	❒	❒	❒	❒	❒	❒	❒	❒	❒	Expected tender price
Project specification	❒	❒	❒	❒	❒	❒	❒	❒	❒	Experience
Project specification	❒	❒	❒	❒	❒	❒	❒	❒	❒	Law and standards
Expected tender price	❒	❒	❒	❒	❒	❒	❒	❒	❒	Experience
Expected tender price	❒	❒	❒	❒	❒	❒	❒	❒	❒	Law and standards
Experience	❒	❒	❒	❒	❒	❒	❒	❒	❒	Law and standards
In the following we ask you to compare the different material options regarding just one single criterion or, in other words, how do the different material options perform considering exclusively this single criterion.										
How do the different material options perform in comparison, regarding the "expected tender price" ?										
Option A	Option A performs dominant better	Very strongly better	Strongly better	Slightly better	Equal performance	Slightly better	Strongly better	Very strongly better	Option B performs dominant better	Option B
Specify conventional concrete	❒	❒	❒	❒	❒	❒	❒	❒	❒	Specify recycling concrete B (concrete rubble aggregates)
Specify conventional concrete	❒	❒	❒	❒	❒	❒	❒	❒	❒	Property specification
Specify recycling concrete B (concrete rubble aggregates)	❒	❒	❒	❒	❒	❒	❒	❒	❒	Property specification

How do the different material options perform in comparison, regarding your "experience with the particular materials"?

Option A	Option A performs dominant better	Very strongly better	Strongly better	Slightly better	Equal performance	Slightly better	Strongly better	Very strongly better	Option B performs dominant better	Option B
Specify conventional concrete	❒	❒	❒	❒	❒	❒	❒	❒	❒	Specify recycling concrete B (concrete rubble aggregates)
Specify conventional concrete	❒	❒	❒	❒	❒	❒	❒	❒	❒	Property specification
Specify recycling concrete B (concrete rubble aggregates)	❒	❒	❒	❒	❒	❒	❒	❒	❒	Property specification

How do the different material options perform in comparison, regarding the existing "law and standards"?

Specify conventional concrete	❒	❒	❒	❒	❒	❒	❒	❒	❒	Specify recycling concrete B (concrete rubble aggregates)
Specify conventional concrete	❒	❒	❒	❒	❒	❒	❒	❒	❒	Property specification
Specify recycling concrete B (concrete rubble aggregates)	❒	❒	❒	❒	❒	❒	❒	❒	❒	Property specification

Which materials were specified in this construction project for wet outdoor structural concrete applications?

- ❒ Conventional concrete
- ❒ Recycling concrete B (concrete rubble aggregates)
- ❒ Property specification
- ❒ I do not know
- ❒ No wet outdoor concrete applications in the project

Were there additional aspects affecting your decision, if yes which ones?

____

____

Which materials were used in this construction project for wet outdoor structural concrete applications?

- ❒ Conventional concrete
- ❒ Recycling concrete B (concrete rubble aggregates)
- ❒ I do not know
- ❒ No wet outdoor concrete applications in the project

Publication II

Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials

Overview

This paper analyses construction stakeholders' behaviours, and decision-making regarding recycled mineral construction materials (RMCM) for the construction material market in Switzerland. It therefore aims at illustrating why construction stakeholders do not yet broadly apply RMCM even though their use is regulated and successful application examples are available. Applying the agent operationalization approach, stakeholders' decision-making was elicited with the analytical hierarchy process (AHP) and quantified together with their behaviour in a survey. The usefulness of the agent operationalization approach is shown by the good alignment of the outcome of decision modelling with reported behaviour.

Main findings

- *Stakeholder interaction:* The results demonstrate the importance of stakeholders' interactions, as most stakeholders decide which material to apply based on interactions with other stakeholders (i.e. recommendations and specifications).
- *The role of the engineer:* An initial specification by awarding authorities that construction should be sustainable had little relevance to subsequent material decisions. Instead engineers, the second stakeholder group in the interaction chain, mainly influenced by experience, law and standards, had a crucial role in influencing the decision chain.
- *Sectorial differences:* In civil engineering (CE) RMCM were broadly accepted where in more than 30% of all cases RMCM were used. In contrast, RMCM were still niche products in structural engineering (SE) with less than 10%.
- *Rational decisions:* Construction stakeholders usually decided rationally (i.e. make consistent judgments in the AHP) and behave rationally (i.e. good alignment of decision-making outcome with behaviour).

Relevance for the doctoral thesis

With respect to the thesis this study contributed with (i) understanding construction stakeholders' reluctance to a broader use of RMCM and (ii) providing empirically based agent decisions for the agent-based model development.

Decisions on recycling: construction stakeholders' decisions regarding recycled mineral construction materials

Knoeri Christof [a,b], Binder Claudia R. [c] , Althaus Hans-Joerg [b]

[a] *Social and Industrial Ecology, Department of Geography, University of Zürich, Winterthurerstrasse 190 , CH-8057 Zürich, Switzerland, christof.knoeri@empa.ch*

[b] *Technology and Society Laboratory, Empa, Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland, hans-joerg.althaus@empa.ch*

[c] *Institute of Systems Sciences, Innovation and Sustainability Research (ISIS), University of Graz, Merangasse 18, 8010 Graz, Austria, claudia.binder@uni-graz.at*

Resources Conservation & Recycling

Received: 20st July 2010 Received in revised form: 9th May 2011 Accepted: 19th May 2011

Abstract

Construction and demolition (C&D) waste, being already the largest waste fraction in industrialized countries, is expected to increase in the future. C&D waste recycling has been considered to be a valuable option not only for minimizing C&D waste streams to landfills but also for preventing primary mineral resource depletion. Even though the use of recycled mineral construction materials (RMCM) is regulated and successful application examples are available, it is not yet broadly applied by construction stakeholders. Thus, far too little is known about stakeholders' reasoning leading to that behavior. We analyze construction stakeholders' behavior, and decision-making regarding RMCM for the construction material market in Switzerland. Applying the agent operationalization approach, stakeholders' decision-making was elicited with the analytical hierarchy process (AHP) and quantified together with the behavior in a survey. The results demonstrate the importance of stakeholder interaction, i.e. most stakeholders decide which material to apply based on interaction with other stakeholders (i.e. recommendations and specifications). However, an initial general specification by awarding authorities that construction should be sustainable has little relevance to the subsequent material decisions. Instead the role of engineers, the second stakeholder group in the interaction chain, mainly influenced by experience, law and standards, is crucial. Furthermore, in civil engineering (CE) RMCM are broadly accepted, whereas in structural engineering (SE) RMCM are still a niche product. The usefulness of the agent operationalization approach is shown by the good alignment of the outcome of decision modeling with observed behavior.

Keywords: Construction & demolition waste, recycled mineral construction materials, recycling behavior, decision-making, analytical hierarchy process, agent operationalization approach

1. Introduction

Construction and demolition (C&D) waste, which already comprises the largest waste fraction in industrialized countries (Schachermayer et al., 2000), is expected to increase in the future. Studies from the Netherlands (Muller, 2006) and Norway (Bergsdal et al., 2007) show this trend for countries of the European Union, Hashimoto et al. (2007) for Japan and Hao et al. (2007) for Hong Kong. Due to limited landfill capacities (Duran et al., 2006) and C&D waste disposals' environmental impacts (Fatta et al., 2003, Jang and Townsend, 2001), a sustainable management of these waste streams is required. C&D waste recycling has been considered to be a valuable option not only for minimizing C&D waste streams to landfills (Lawson et al., 2001) but also for preventing primary mineral resource depletion (e.g. Blum and Stutzriemer (2007) and Weil et al., (2006)).

In Switzerland C&D waste is by far the largest waste fraction (~70% (FOEN, 2005), and it is dominated by the mineral fraction with 85% (FOEN, 2001a). Although the recycling rate of mineral C&D waste is currently rather high at about 80%, (FOEN, 2005), it varies across the country (FOEN, 2001b, Staeubli et al., 2005). Moreover, it is expected to decrease due to a decreasing demand for recycling mineral construction material (RMCM) from civil engineering (CE), and an increasing amount of C&D waste from structural engineering (SE) (Spoerri et al., 2009). In the following we consider civil engineering (CE) as the design and construction of mainly publicly contracted works, such as roads, bridges, tunnels water and electricity supply and sewerage, and structural engineering (SE) as the design and construction of buildings.

The current RMCM recycling routes (mainly low-grade applications, lean concrete and uncompounded foundation layers), have limited capacities (Moser et al., 2004). Recent research has demonstrated the suitability of RMCM for high-grade applications (Hoffmann and Jacobs, 2007, Li, 2008, Poon et al., 2009, Rao et al., 2007). High-grade RMCM applications are already defined in laws (FOEN, 2006) and standards (KBOB, 2007, SIA, 2010). In addition, reference projects have demonstrated the practicability of high-grade RMCM applications (Hofmann and Patt, 2006).

Even though RMCM are technically feasible and regulated, and successful application examples are available; they are not yet broadly used in Switzerland. In particular SE stakeholders still use conventional materials for high-grade applications. There may be two reasons for this: there are too few or no economic incentives for a behavioral change towards recycling (Huang et al., 2002, Loughlin and Barlaz, 2006), and there is a cognitive bias not to change established behavior (i.e. status quo bias) (Kahneman et al., 1991).

Prices for RMCM alternatives are often in the same range as conventional materials (Robinson et al., 2004). A comparison of prices ex works of two large concrete producers in Switzerland showed that the recycling discount varied from a 7% reduction to a price that was 2% higher (EBERHARD, 2010, HASTAG, 2010). This finding reflected the fact that price differences related to the different mineral construction materials are often negligible in the overall project costs.

Thus, decision criteria other than price are likely to tip the balance in construction stakeholders' decisions regarding RMCM; legitimation rules (e.g. construction laws and standards, scope of liability, image and trends), authoritative resources (e.g. policy objectives, project specifications, recommendations) as well as allocative resources (e.g. experience) may be important (Knoeri et al., 2010, Moser et al., 2004). Therefore, knowing the decision criteria and their respective potential for affecting decisions is crucial for quantitatively analyzing decisions regarding RMCM.

Decision heuristics of managers (e.g. decision-making under uncertainty (Amihud and Lev, 1981, Finucane et al., 2000)) and adherence to the status quo (Pettigrew, 1973) may cause lock-in effects, preventing emerging technology adoption (Witt, 1997). Using tried-and-tested simple decision heuristics has been found to be usually more efficient than rationally reflecting on the different alternatives and criteria (Schwenk, 1984, Simon, 1979). Individuals utilize biases and heuristics to different degrees according to different roles (e.g. managers vs. entrepreneurs) (Busenitz and Barney, 1997). Construction stakeholders' decisions vary from ownership requirements (awarding authority) via design specifications (architects) to risk related decisions (structural engineers and contractors) (Knoeri et al., 2010). Thus, it is important to know how rational construction stakeholders take their decisions and which decision heuristics they use when.

Summarily, the criteria affecting each decision, the strength of the criteria as well as which decision heuristics stakeholders use have to be analyzed, in order to understand how to overcome a construction stakeholder's reluctance to use RMCM. The purpose of this paper is to analyze construction stakeholders' behavior and decisions regarding RMCM by answering the following research questions:

- How do construction stakeholders behave (i.e. what construction materials do they apply)?
- What decision criteria contribute to what extent to the construction stakeholders' decisions regarding RMCM?
- How rationally do construction stakeholders make their decisions and behave?

This paper first presents the methods used, gives insight into the case study area (i.e. the Swiss construction material demand) and describes the sample. Secondly, we present the results regarding the research questions raised above per construction sector and stakeholder group. Thirdly, we discuss the findings and their practical implications in the broader research context. Finally, we conclude and give an outlook on further research.

2. Methods and case study and sample description

2.1 Methods

2.1.1 The agent operationalization approach

In order to analyze construction stakeholders' decision-making and behavior regarding RMCM we used the agent operationalization approach for agent based modeling (Knoeri et al., 2010). It includes the following four steps: (i) identification of the relevant agents, (ii) identification of the agents' interaction chain, (iii) quantification of agents' decision-making process and (iv) behavioral consistency analysis and conceptual validation. For step one and two we relied on Knoeri et al. (2010) and concentrated on steps three and four of the agent operationalization approach for (iii) quantifying Swiss construction stakeholders' decision-making process, (iv) analyzing its consistency with their behavior and conceptually validating the decision-making presumptions. While doing so, we collected decision-making data, based on the analytical hierarchy process (AHP), and behavioral data in a paper-based survey.

2.1.2 Analytical hierarchy process (AHP) for decision-making analysis

We adopted the multi criteria decision analysis (MCDA) (Mendoza and Martins, 2006) method analytical hierarchy process (AHP) for analyzing stakeholders' decision-making process (Knoeri et al., 2010). In contrast to the AHP proposed by Saaty (1980, 1990) information was gathered from different sources (i.e. literature review, expert interviews and workshops and a survey).

First, the decomposition of the decision-making process (i.e defining decision goal, alternatives and criteria) was done in a literature review, combined with 14 expert interviews according to Mieg and Naef (2006) (i.e. three architects, two structural and two civil engineers, tree contractors, three public and one commercial awarding authority) and validated in a consensus building expert workshop according to Susskind et al. (1999). Secondly, the comparative judgments of the different alternatives and criteria were collected in a survey with written questionnaires according to Diekmann (2007). Third, the final AHP synthesis (i.e. synthesis of the judgments to an overall alternative preference, and consistency analysis of the judgments) was done again according to the standard AHP procedure (Saaty, 1980, 1990).

2.1.3 Behavioral consistencies and conceptual validation

The behavioral consistency analysis allows one to assess how rationally stakeholders behave and the conceptual validation for how rationally they make their decisions.

The behavioral consistency was analyzed by comparing the best performing alternative from the decision-making process with the reported behavior. We considered stakeholders' behavior as rational when they chose the best performing alternative from their decision-making processes. This did not necessarily mean that stakeholders behaved in a fully rational fashion with complete knowledge about their environment (Simon, 1955). They may display "bounded rationality", which means they are limited in processing the information used in the decision-making process (Kahneman, 2003, Simon, 1955, 1979). However differences often appeared between the preferred alternative (i.e. intention (Ajzen, 1991)) and behavior, caused by external (i.e. contextual factors) and internal drivers (i.e. habit and psychological arousal) (Feola and Binder, 2009, Triandis, 1980).

The conceptual validation of the AHP assumption of reflected decisions according to Svenson (1979, 1996), where decision-makers are cognizant of some balance between known alternatives and decision criteria, was done with the consistency analysis of the judgments in AHP. In rationally reflected decisions a great amount of cognitive effort is included (Jungermann et al., 1998) as required by the AHP pair-vice comparative judgments (Forman and Gass, 2001). We therefore considered the consistency ratio (CR) as proposed by Saaty (1980) as a measure of cognitive effort in the decision. Therefore, stakeholders with highly inconsistent judgments may process decision information less rationally and use simpler decision heuristics. We derived the consistency ratio (CR) as proposed by Saaty (1980) by comparing the consistency index (CI) with the random consistency indices (RI) calculated by Aquaron and Moreno-Jimenez (2003). In the standard AHP procedure judgments are considered inconsistent with a CR higher than 10% (Saaty, 1980). Due to the predefined criteria and alternatives higher inconsistencies were expected.

2.1.4 Survey

Sample selection: A random sample was selected for each of the nine stakeholder groups. We used two methods according to the accessibility of the stakeholder's addresses. The addresses of public awarding authorities, architects, contractors, structural and civil engineers' were randomly selected one by one from the official Swiss telephone directory in the case study area. The addresses of private and commercial awarding authorities were selected from the building permit publications in the official register for 2006 in selected communities. The communities were randomly selected with higher probability according to their construction investment (i.e. probability proportional to size selection). This avoided hypothetical answering from stakeholders who were not involved and ensured that the fastest developing construction areas would be included.

Questionnaire structure: The questionnaire was structured in three parts as follows:

- First, questions related to the currently finished construction project (i.e. investment sum, type, purpose, mode of construction, and distance to residence/office) were asked.
- Second, stakeholders' decision-making and behavioral data were gathered in chronological order for the stakeholder groups with several decisions. Each decision was introduced with a detailed description of the material application affected, the alternatives available, and the decision-criteria considered. Subsequently, stakeholders were asked to weight the criteria and alternatives per criterion in pair-wise judgments. Following each decision, we gathered data about the actual behavior (i.e. decision taken).
- Third, socio-demographic data (i.e. age, gender, education and income) were collected.

Procedure: The survey was conducted between July 2008 and August 2009 in two studies, in the German and French parts of Switzerland, respectively. The questionnaires were sent by postal mail to the selected addresses. Follow-up calls were conducted in stakeholder groups with low response rates. Participants in the French part of the country were given an additional opportunity of answering the questionnaire online. A total of 424 valid questionnaires were received, which corresponded to a response rate of about 11%.

2.2 Case study

2.2.1 Case study area

We chose the four cantons, Zurich (ZH), Berne (BE), Geneva (GE), and Vaud (VD) as case study areas according to three criteria: (i) culture, (ii) rural-urban distribution and (iii) construction investment. In different cultural and rural or urban cantons, different behavior of construction stakeholders regarding RMCM was hypothesized.

(i) Culture: Several cultural differences other than language were observed between the German and French speaking parts of Switzerland. For example, environmental issues are of higher concern in the German part (*i.a.* ZH, BE), whereas the French part (i.a. GE, VD) is more liberal for the adhesion to the Europe Union (Buechi, 2000). Hence, we expected higher acceptance of RMCM in the German part.

(ii) Rural-urban distribution: We expected higher usage of RMCM in the densely populated urban cantons (i.e. ZH, GE, with 74% and 93% urban communities respectively) than in the rural cantons, where primary mineral resources and depositories were less scarce and secondary mineral resources were less abundant (i.e. BE, VD with 78% and 67% of rural communities) (Hotz and Weibel, 2005).

(iii) Construction investments: we ensured the broadest system coverage by considering the cantons with the most construction activities (i.e. investment sums). Since 1987 countrywide and in the German part of Switzerland, the largest construction investments have been made in ZH and BE (~ 30%). GE and VD had the highest investments in the French-speaking part of Switzerland, although nationally considerably lower (~10%) than ZH and BE (BfS, 2008a).

The case study area comprised 43% of the Swiss population (BfS, 2008d) and covered 39% of the Swiss settlement area (Hotz and Weibel, 2005) in addition to the aforementioned properties attributed to it. Therefore, the sample area covered about 40% of the federal construction investments, inhabitants and settlement area. Furthermore, the selection of rural and urban as well as German and French speaking cantons allowed us to do a more sophisticated result extrapolation, whenever differences were found.

2.2.2 Swiss construction stakeholder interaction chain

Knoeri et al. (2010) identified awarding authorities, structural and civil engineers, architects and contractors as key stakeholder groups. Their interaction was operationalized as an interaction model with multiple involvements of the awarding authorities.

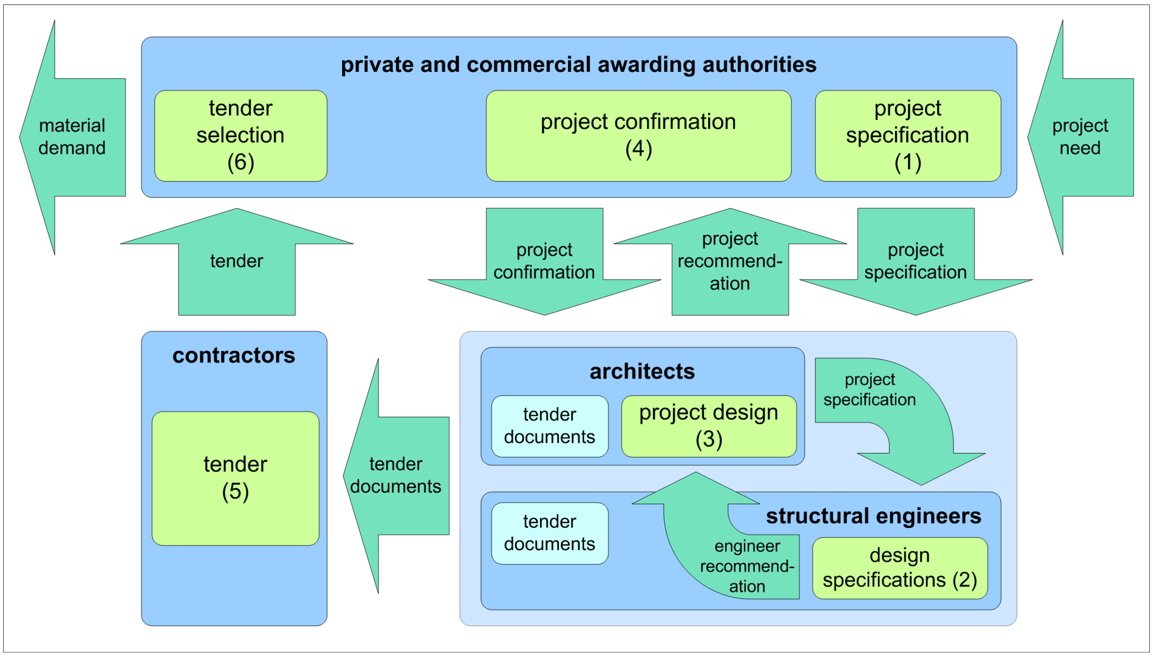

Figure 1: Model of the SE stakeholder interaction chain (private and commercial awarding authorities) (blue boxes indicate the agents, light green boxes their decisions and green arrows the interaction) (Knoeri et al., 2010).

Figure 1 illustrates the interaction chain in SE. Awarding authorities make general specifications about sustainable construction in the initial *project specifications (1)*. This *project specification (1)* is forwarded to the structural engineers by the architects. Subsequently structural engineers make their *design specifications (2)*, and architects recommend their *project design (3).* This project recommendation is reviewed and *confirmed (4)* by the awarding authorities, and specified in the tender documents. Contractors submit their tender (5) among which awarding authorities finally select the preferred tender (6). Please see Knoeri et al. (2010) for details. Public awarding authorities specify the criteria for the tender selection together with the project confirmation as they are required to do in government procurement.

In CE stakeholder interaction is slightly different from SE. Most projects are from public awarding authorities. Therefore, the final tender selection criteria are predefined and published with the project confirmation. Further, civil engineers make the design specifications and the project design, taking the role of architects and structural engineers.

2.2.3 Stakeholder decision alternatives

Awarding authorities had the option of making a general sustainable construction specification (SCS), explicitly specifying RMCM or making no specification concerning sustainable construction (NSCS) in the initial *project specification (1)*. In the subsequent *material specific decisions (2-6)*, we determined the decision-making for three application levels in each construction sector. Consequently, different material alternatives were specified for each application according to the applicable laws and standards. The recycling options in SE were primarily defined by the Swiss engineers' and architects' association (SIA, 2010), the federal office for the environment (FOEN, 2006) and the recommendation from the coordination office for federal estate management (KBOB, 2007). The Swiss association of road and transportation experts (e.g. (VSS, 1998a)) set the standards in CE.

For SE one conventional material alternative and one recycling alternative were defined. According to the experts, RMCM are more widely accepted in CE than in SE. We therefore specified an additional third material alternative for CE, which had not yet been accepted and gave an opportunity to link the two sectors by using waste material (i.e. concrete and mixed rubble aggregates (Table 1)) from SE in CE. In addition to the material alternatives specified in Table 1 an option was given to specify material properties rather than materials. This gave stakeholders the option to pass on the material decision to the next stakeholder in the interaction chain.

Table 1: Applications, material alternatives, their description and the corresponding laws and standards

sector	application	material alternative	description	law/standard
Structural engineering	outside concrete	- conventional concrete - recycled concrete B	primary material aggregates (>80%) concrete rubble aggregates (25-100%)	(FOEN, 2006, KBOB, 2007, SIA, 2010)
	inside concrete	- conventional concrete - recycled concrete M	primary material aggregates (>80%) mixed rubble aggregates (25-100%)	
	lean concrete	- conventional concrete - recycled concrete M	primary material aggregates (>80%) mixed rubble aggregates (25-100%)	
Civil engineering	bonded sub base	- conventional gravel-sand	primary material aggregates	(VSS, 1998a)
		- recycled gravel-sand P	road demolition debris aggregates (>95%)	(VSS, 1998e)
		- recycled gravel-sand A	roads demolition aggregates (>80%) asphalt pavement aggregates (<20%)	(VSS, 1998b, e)
	unbonded sub base	- conventional gravel-sand	primary material aggregates	(VSS, 1998a)
		- recycled gravel-sand B	road demolition debris aggregates (>80%) concrete rubble aggregates (<20%)	(VSS, 1998c, e)
		- mixed rubble aggregates	mixed rubble aggregates(<97%)	(VSS, 1998d)
	lean concrete	- conventional concrete - recycled concrete B - recycled concrete M	primary material aggregates (>80%) concrete rubble aggregates (25-100%) mixed rubble aggregates (25-100%)	(FOEN, 2006, KBOB, 2007, VSS, 1998c, d)

2.3 Sample description and discussion

A detailed sample description is provided in Appendix A in Table A.1 and Table A.2. In the following we show the samples sizes of the nine stakeholder groups and present and discuss their construction related (i.e. project size, distance to construction site and construction frequency), spatial (i.e. cantonal and rural-urban) and socio-demographic characteristics.

Sample size: Table 2 shows the sample size of each stakeholder group per construction sector and linguistic region. Whereas the sizes of the overall Swiss sample (i.e. mean of 46) and the

German part sample (i.e. mean 35) are adequate, the size of the French part (i.e. mean 11) limits us in making a comparison between the cultural regions.

Table 2: Sample size in the different construction sectors (i.e. structural engineering (SE) and civil engineering (CE)) **and linguistic regions of Switzerland** (number of valid questionnaires received)

stakeholder groups	region / construction sector	**French part of Switzerland** (GE + VD) SE	CE	**German part of Switzerland** (ZH + BE) SE	CE	**Swiss sample** (GE, VD, ZH, BE) SE	CE
public awarding authorities		8	7	27	43	35	50
private awarding authorities		15		35		50	
commercial awarding authorities		4		37		41	
structural/civil engineers		19	11	51	31	70	42
contractors		9	1	40	22	49	23
architects		24		30		54	

Project size: The size of the construction project was measured as the sum invested. In SE the majority (>66%) of projects sums in the sample exceeded the one million Swiss francs limit, with the exception of the private awarding authorities. The prerequisite of having built with mineral construction material (MCM) may have excluded small refurbishing projects without MCM and therefore may have lead to larger project sums in the sample. In CE, where most projects include MCM, the projects were slightly smaller.

Distance to construction site: The distance to the construction site shows that stakeholder interaction in the construction sector happens at a rather small scale (i.e. median of about 5km). Furthermore, a clear difference between the distances to the construction sites of construction experts (i.e. architects, structural and civil engineers and contractors) (5 - 15km) and those of awarding authorities (0.3 - 3 km) was observed.

Construction frequency: Similar to the distances to construction site, construction experts do significantly more construction projects (five to ten projects per year) than the awarding authorities with less than one project per year. In addition, in SE 78% of the private awarding authorities had just one project built in the last five years, in contrast to the commercial (about one project per year) and the public awarding authorities (two to three projects a year (median).

Spatial characteristics: In SE the stakeholder frequencies (i.e. number of stakeholders) in cantons and rural and urban communities in the sample aligns well with the corresponding construction activities (i.e. construction investments (BfS, 2008a)). In CE stakeholders from the French part as well as from rural communities are underrepresented.

Socio demographic data: The socio-demographic data gathered (i.e. age, gender, education and income) were compared with the working population (BfS, 2008c, d) and the Swiss household incomes (BfS, 2008b). Construction stakeholders were significantly older (i.e. higher frequencies in the age groups above 40) than the working population with the exception of civil engineers and contractors. This can be explained by the large investment sums involved in construction activities where mainly seniors take responsibility. The same holds true for education and income, which both were generally higher than in the working population in the case study region. As expected, the construction business is still “a man’s world” (more that 83% male).

3. Results

3.1 Construction stakeholders' behavior regarding RMCM

3.1.1 Stakeholder behavior in structural engineering (SE)

Figure 2 shows the behavioral frequencies of construction stakeholders in SE arranged in their interaction chain. A majority of the private awarding authorities (57%) specified sustainable construction (SCS) at the beginning of the construction process (1), whereas RMCM was explicitly asked for rather seldom (8%). The first material specific decision (e.g. design specification (2) of structural engineers) showed a completely different picture with a clear dominance for conventional materials decreasing towards low-grade applications (93-73%). The subsequent project design (3) from the architects mainly followed the engineers' recommendations (86-60%), although recommending more the property specification. Private awarding authorities mainly confirmed (4) the architects' recommendations for conventional materials (71-63%). This project confirmation (4) was translated into the tender documents either by the architect or the structural engineer and sent to the contractors. For the tender (5), they clearly differentiated between the structural and lean concrete applications. Whereas for the latter equal frequencies for the recycling (56%) and the conventional (44%) option were observed, almost exclusively (>91%) conventional materials were tendered for the former. Private awarding authorities preferred mainly conventional materials in the final tender selection (6) decision (93-87%) (Figure 2).

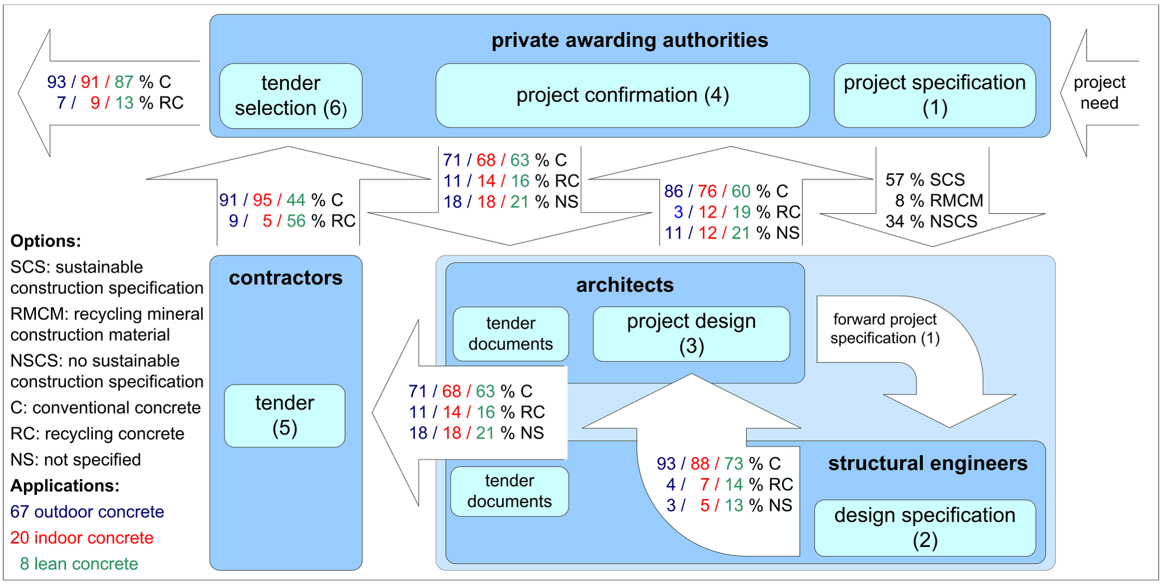

Figure 2: Behavioral frequencies in structural engineering (The applications are indicated in color for material specific decisions (e.g. 2-6)).

Public awarding authorities more often preferred the recycling option, with less conventional material in the project confirmation (4) (59-47%) and in the tender selection (6) (81-74%), than private and commercial awarding authorities. Between the latter, no significant differences were found in all three of their decisions (1, 4 and 6).

3.1.2. Stakeholder behavior in civil engineering (CE)

Firgure 3 shows the behavioral frequencies of construction stakeholders in CE arranged in their interaction chain. Stakeholders in CE chose the RMCM option in about one third of the cases throughout the construction process, with the exception of the initial project specification (1). In addition, the differentiation between application levels and different recycling materials indicated the knowledge and experience with RMCM in the CE sector. However, recycling materials from SE (i.e. recycling concrete B and mixed rubble aggregates) were not yet accepted nor applied in CE.

In CE public awarding authorities do not often (16%) specify sustainable construction in general (SCS) in the initial project specification (1). Usually no specifications regarding sustainable construction were made (64%) or whenever they were, RMCM were directly requested (20%). Civil engineers recommended conventional materials in 47-58% of the cases, recycling materials in 24-30% of the cases (i.e. option 2 and 3) and specify properties in 13-29% of the cases in the project design decisions (2). The overall proportion of the three options (i.e. conventional (1), recycling (2 and 3) and property specification (4)) did not differ much among the applications in contrast to the preferred type of recycling material, which clearly depended on the application. The same holds true for the project confirmation (3) of the awarding authorities, mainly following the engineers' recommendation. Civil engineers forwarded the received project confirmation in the form of tender documents to the contractors. The contractors' tender (4) had the highest recycling frequencies with about 50% across the applications. Finally, awarding authorities demanded 30-39% recycling materials in their tender selection (5) (Figure 3).

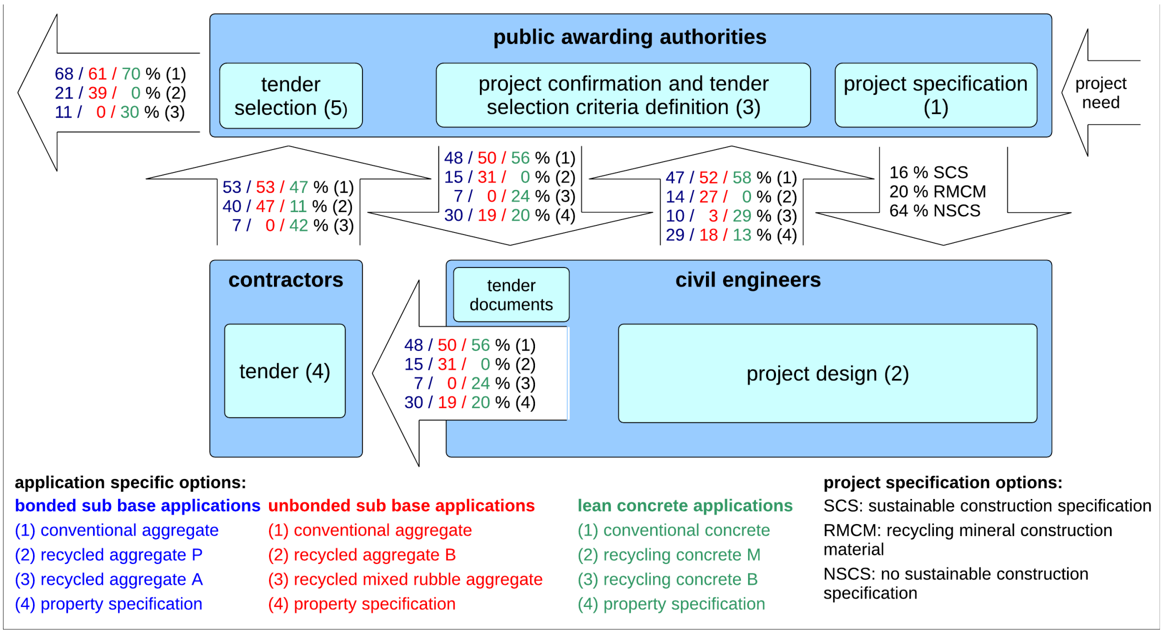

Figure 3: Behavioral frequencies in civil engineering (applications are indicated in color for material specific decisions (e.g. 2-5)).

3.2 Construction stakeholders' decision criteria

3.2.1 Stakeholder decision criteria in structural engineering (SE)

A detailed description and definition of the decision criteria in SE is provided in Appendix B in Table B.1. In SE all construction stakeholders considered economic criteria and the outcomes of any previous decisions (e.g. specification, recommendations) in each of their decisions. Economic criteria were general economic aspects, expected costs, marketability or explicit prices. The trends and image of RMCM appeared in several decisions as a criterion, though primarily at the beginning of the stakeholder interaction chain. The same held true for social aspects, whereas ecological aspects were considered throughout the process. Technical aspects were more frequently included towards the end of the stakeholder interaction chain.

Private, commercial and public awarding authorities (AA) considered different aspects in their decisions or defined the criteria differently. Social aspects for private and public AA included the social desirability and political objectives for the latter, in addition to image and trends, which were considered by all AA in the initial project specification (1). Private and commercial AA considered technical aspects, whereas only private AA took ecological aspects into account in the project confirmation (4). The personal image of RMCM was a criterion for commercial and public AA, the former additionally included marketability aspects and the latter considered policy objectives. The largest differences exist in the criteria considered between private and commercial AA on the one hand and public AA on the other hand in the final tender selection (6). This is due to the restriction of public AA to government procurement. Thereby the tender selection criteria have to be predefined and communicated. In addition to the tender price, private and commercial AA considered the tender documents and technical aspects. Marketability was solely taken into account by commercial AA. Ecological aspects were considered by private and public AA, with the private AA understanding the general ecological performance of the project, whereas the public AA meaning transport distances and the companies' ecological performance. Public AA also specified the company's quality management, company and staff references and education as selection criteria.

3.2.2 Stakeholder decision criteria in civil engineering (CE)

A detailed description and definition of the decision criteria in CE is provided in Appendix B in Table B.2. In CE stakeholders basically considered the same criteria as in SE. However, demolition and disposal costs were included in addition to the economic considerations of the construction experts (i.e. engineers and contractors). Technical aspects had already been included in the project specification (1) by the AA. Furthermore, for contractors the tender selection criteria were a criterion, as most projects were from public AA. Consequently public AA used the same criteria as their colleagues in SE in the final tender selection (5).

3.3 Construction stakeholders' decision-criteria weights

In the following the weighted criteria are presented as the mean of the three applications, as no significant differences were found in the criteria weighting among the applications.

3.3.1 Stakeholders decision criteria weights in structural engineering (SE)

Figure 4 shows the mean of the criteria weights for the construction stakeholder interaction chain in SE. The interaction criterion (i.e. recommendation or specification from previous stakeholder) is the most important criterion in each material specific decision (3-6), with the exception of the structural engineers' design specification (2), which is mainly determined by law, standards and experience. By contrast, the awarding authorities' initial project specification (1) weighted little in structural engineers' (2) and architects' (3) decisions, as already indicated by the behavior.

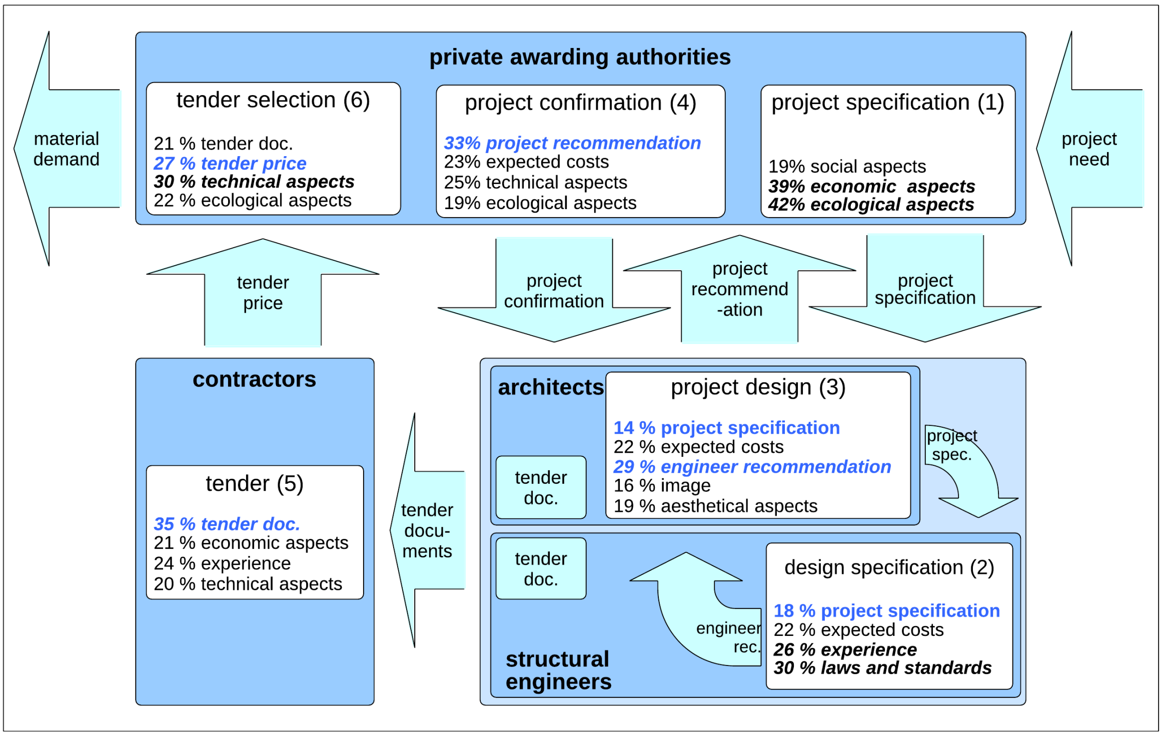

Figure 4: Decision criteria weights in SE from private awarding authorities, structural engineers, architects and contractors (mean) (Bold/italics criteria indicate significant higher importance for the particular decision; interaction criteria (e.g. engineer recommendation for the architects' project design) are indicated in blue.

Private awarding authorities' initial project specification (1) was mainly influenced by economic (39%) and ecological aspects (42%), whereas social aspects played a minor role. Structural engineers primarily considered laws and standards (30%) and their experience (26%) in their design specification (2), little influenced by the awarding authorities' project specification (18%). For the architects' project design (3) the engineers' recommendations were most important (29%) followed by the expected costs (22%) and aesthetic aspects (19%); the project specification again was less important (14%). In the subsequent project confirmation (4), private awarding authorities relied to a large extent on the architects' recommendation (33%). Furthermore, they considered technical aspects (25%) and the expected costs (23%), whereas ecological considerations were the least important (19%). Contractors considered the tender documents to be most important (35%), followed by economic aspects (21%), technical aspects (20%) and their experience with RMCM (24%) (5). For the private awarding authorities' final tender selection (6), tender price (27%) and technical aspects (30%) were the deciding factors (Figure 4).

Table 3 shows the difference of the awarding authorities' decision criteria weighting. They did not differ strongly in the criteria weights for their project specification (1), whereas commercial AA gave less importance (29%) to ecological and more to social aspects (30%). In the project confirmation (4) though, besides considering different criteria, AA gave different weights to the criteria. Commercial AA gave most weight to technical aspects (24%) and marketability (24%) in contrast to the private AA. Public AA considered the criteria in a more balanced fashion, although the architects' project recommendation (29%) and the expected costs (28%) tended to be more important than image (22%) and political aspects (21%). Private and commercial AA differed most from the public AA in the final tender selection (6). For private and commercial AA tender price and technical aspects were the decisive criteria. Commercial AA considered marketability and private AA ecological aspects third priority. Public AA predefined and communicated their selection criteria, which were clearly dominated by the tender price.

Table 3: Decision criteria weights in SE for the three awarding authority groups and their decisions (Bold/italics criteria indicate significant higher importance that other criteria)

decision	**decision criteria**	**Awarding authorities**		
		private	**commercial**	**public**
project specification (1)	• social aspects	19%	30%	26%
	• economic aspects	**39%**	**41%**	**39%**
	• ecological aspects	**42%**	29%	**36%**
project confirmation (4)	• project recommendation	**33%**	19%	29%
	• expected costs	23%	21%	28%
	• technical aspects	25%	**24%**	-
	• ecological aspects	19%	12%	-
	• marketability	-	**24%**	-
	• image	-	-	22%
	• political aspects	-	-	21%
tender selection (6)	• tender documents	21%	16%	-
	• tender price	**27%**	**29%**	**75%**
	• technical aspects	**30%**	**33%**	-
	• ecological aspects	22%	-	2%
	• marketability	-	22%	-
	• quality management	-	-	10%
	• company references	-	-	10%
	• staff references	-	-	1%
	• education	-	-	2%

3.3.2 Stakeholders' decision criteria weights in civil engineering (CE)

Figure 5 shows the mean of the criteria weights for the construction stakeholder interaction chain in CE. Civil engineers' design specification (2) as determined by law and standards, experience and economic considerations stands at the beginning of a decision chain, whereas in the subsequent decisions (3.1, 4, 5) the interaction criteria were most important. The awarding authorities' initial project specification (1) had almost no impact on the application specific project design decision (2).

In the initial project specification (1) of public awarding authorities, technical (35%) and economic aspects (27%) were most important, whereas ecological (22%) and social aspects (16%) had minor importance. Civil engineers decided in the project design (2) mainly based on law and standards (33%), expected costs (26%) and experience (27%). The project specification (14%) was hardly considered at all. The public awarding authorities confirmed the project (3.1) by considering basically project recommendation (32%) and expected costs (29%). Contractors' tender (4) was generally driven by the interaction (i.e. selection criteria and tender documents 42%), while further experience technical and economic aspects were involved (about 20% each). According to government procurement rules, public awarding authorities had to predefine the selection criteria for the tender selection (5). Thereby the tender price (75%) dominated the decision, whereas quality management and company references had minor influence. Staff references, education and ecological aspects had negligible influence on the tender selection.

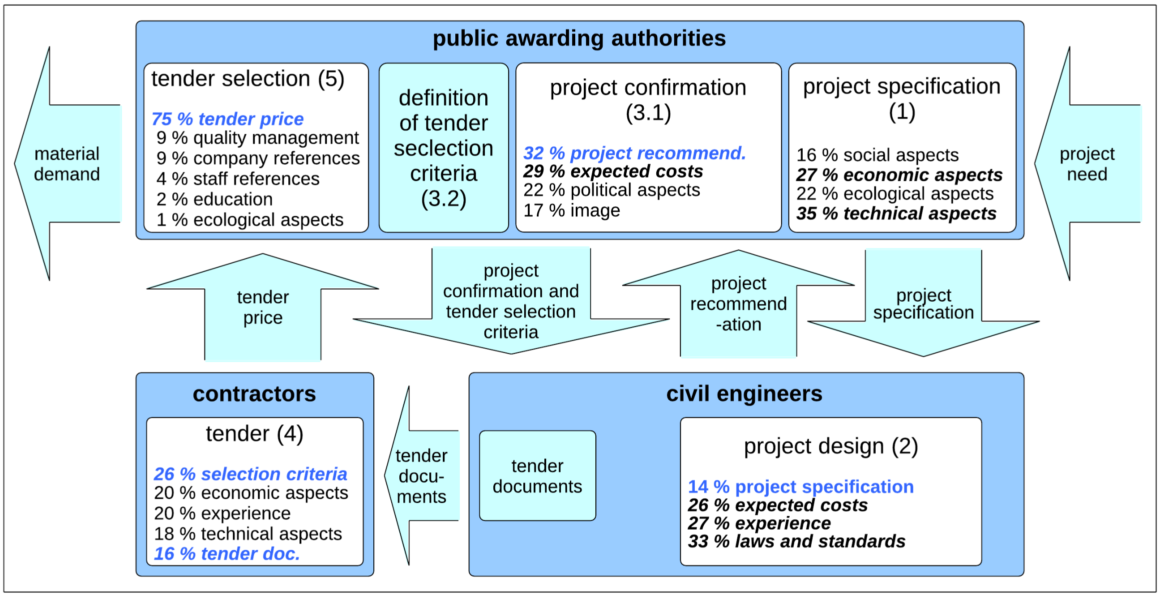

Figure 5: Decision criteria weights in civil engineering from public awarding authorities, civil engineers and contractors (mean) (Bold/italics criteria indicate significant higher importance for the particular decision; interaction criteria are indicated in blue.

3.3. Rationality of behavior and decision-making

Behavioral consistencies: A majority (74%) of the stakeholders behaved rationally with consistent decision-making and behavior. This varied among the stakeholder groups and their decisions. Awarding authorities were less consistent with behavior in the rather general project specification (1) decision (68%) than in the subsequent project confirmation (4) (78%). While construction experts in SE showed high behavioral consistencies (84%), civil engineers' and CE contractors' decisions were less consistent with their behavior (63%) (Table 4). In SE for awarding authorities' final tender selection (6) not all alternatives were weighted per criterion (e.g. the unknown tender price for different material options). Therefore, it was not possible to assess the best performing alternative and subsequently the behavioral consistency.

Conceptual validation: Most stakeholders made rational decisions. The AHP presumption of carefully reflected decisions was generally confirmed because most of the judgments were made consistently. The median of the inconsistencies was about 24% in the criteria and 17% in the alternative weighting. Generally, construction experts (i.e. engineers, architects and constructors) made slightly more inconsistent judgments (i.e. 30% in SE and 19% in CE) than awarding authorities (i.e. 18% in SE and 13% in CE). Furthermore, CE stakeholders showed less inconsistent judgments (14%) than stakeholders in SE (23%) (Table 4).

Table 4: Judgment consistency ratios (CR) and behavioral consistency with decision per construction sector, stakeholder group and decision ((i) only criteria weighting available).

sector	stakeholder group	decision	judgment CR [median] weighting of the criteria	judgment CR [median] weighting of the alternative	behavioral consistency [frequency]
structural engineering	awarding authorities	project specification (1)	0.23	0.25	70%
		project confirmation (4)	0.22	0.09	78%
		tender selection (6) (i)	0.21	-	-
	structural engineers	design specifications (2)	0.44	0.24	77%
	architects	project design (3)	0.27	0.12	84%
	contractors	tender (5)	0.37	0.34	90%
civil engineering	public awarding authorities	project specification (1)	0.18	0.14	62%
		project confirmation (3.1)	0.14	0.04	75%
	civil engineers	project design (2)	0.25	0.12	57%
	contractors	tender (5)	0.25	0.13	69%

3.4 Regional differences

We present next the regional differences found (i.e. between rural and urban communities, cantons and the *regional behavioral differences).* Construction stakeholders tended to select more frequently the recycling material option in communities close to cities. This behavior varied among the stakeholder groups and the construction sectors. In SE, only awarding authorities showed a clear tendency for recycling friendlier behavior in agglomerations or central city communities. In CE, civil engineers as well as contractors preferred more RMCM in agglomeration communities than in central city or rural communities. Regarding linguistic regions as well as between rural and urban cantons, individual differences were found, but no general pattern was observed.

Regional differences in the weighting of decision criteria: No general trend between regions was observed regarding the importance of stakeholders' decision criteria. Nevertheless, regional different criteria weighting was found for some stakeholder groups and decisions. For example, social aspects were more important in SE project specification (1) for awarding authorities in rural cantons than in urban cantons.

4. Discussion

This paper has presented construction stakeholders' behavior regarding RMCM and has showed how different criteria contribute to the underlying decisions and how rational construction stakeholders make their decisions and behave.

In the following section, we will first discuss why a sustainable construction specification does not lead to RMCM recommendation; secondly, we will elaborate on the engineers' role at the beginning of the material decision interaction and thirdly, we will outline how rational construction stakeholders decide and behave. Furthermore we will highlight differences between the construction sectors, discuss the potential of and limitations to the approach and make policy recommendations.

4.1 Specifying sustainable construction is not recommending RMCM

Most awarding authorities' initial specifications for sustainable construction are of little to no relevance for their own and construction experts' subsequent material decisions in SE. The first material and application specific decision is made by structural engineers (e.g. design specification (2)) and is the reference for construction stakeholders' behavior regarding RMCM in SE. Consequently, almost exclusively conventional materials were demanded. There may be two reasons for this:

A first reason might be that awarding authorities link sustainable construction primarily to energy issues. This is suggested by the energy focus of the most popular sustainable construction labels in Switzerland MINERGIE (AMI, 2010c), with over 15700 certified buildings (AMI, 2010a). Although the new sub-label MINERGIE-ECO requires inter alia the use of recycling materials, it is not yet widespread and the relation between sustainable construction and recycling mineral materials may not be recognized yet by most of the awarding authorities. However, an increased use of labels incorporating the use of RMCM might increase the importance of the awarding authorities' project specification on the subsequent material decisions.

A second reason might be that structural engineers are responsible for the static integrity of the construction. The high repair costs in case of the collapse of buildings because of miscalculations or risk seeking behavior, is preventing the adoption of new technologies (Witt, 1997) and increasing structural engineers' adherence to the status quo by continuously using established (i.e. conventional) materials.

4.2 The role of the engineers and economic considerations

The role of engineers: Construction stakeholders' material decisions (i.e. all decisions except the initial project specification) are influenced mainly by the interaction with earlier stakeholders in the decision chain. In both construction sectors, engineers' design specifications stand at the beginning of this interaction chain in which the interaction criterion always weights most. Engineers are mainly influenced by law, standards, their experience and economic considerations in CE underlining their responsibility as highlighted under Item 4.1 above. Their reference to law and standards restricts their product liability on the one hand, and on the other hand the great importance of experience indicates their adherence to the status quo. This confirms the critical roles of law and standards for the demand of RMCM as found by Spoerri et al. (2009).

Economic considerations: Economic aspects are taken into account in each decision about RMCM, but are not the most important ones. This is contradictory to the widespread opinion that the cheapest technical feasible option will be applied (Uebersax, 2005). However, it is equally well recognized that criteria other than economic ones (e.g. experience or the image of RMCM) may impact the decision whether to use RMCM (Moser et al., 2004, Spoerri et al., 2009). Regarding sustainable construction in general, we can say that economic considerations are more important (i.e. awarding authorities' project specification in SE) than in the subsequent material specific decisions. This is so because of the large share of building operation costs attributable to energy costs, and the short pay back time of investments in energy measures, for example in insulation, as shown by Eberhard and Martin (2003).

4.3 Rational decisions and behavior

We found that stakeholders make their decisions rationally. This was shown by reasonably consistent judgments in the AHP procedure. The less consistent judgments (inconsistency ratio of ~20%) compared with the accepted 10% in the AHP standard procedure (Saaty, 1980) can be explained by predefined decision criteria and alternatives, whereas decision-makers individually define their criteria and alternatives in AHP standard procedure. That is to say that most stakeholders take carefully reflected decisions where they seek a cognizant balance among given alternatives regarding different criteria (Svenson, 1979, 1996), which is a requirement for MCDA approaches (Mendoza and Martins, 2006). Construction experts with slightly higher inconsistencies may violate this assumption by using simpler decision heuristics (Johnson et al., 1988, Jungermann et al., 1998). This may be explained by the fact that they are more frequently involved in construction than awarding authorities are, thus leading to the former making more decisions in a more routine manner.

Most stakeholders (74%) behave rationally by choosing the preferred alternative when making decisions. This demonstrates the usefulness of the decision-making quantification with AHP. The results show that even for the stakeholder group with the least rational decision-making (i.e. SE contractors with 36% inconsistency in their judgments) the consistency with behavior is high (90%). Thus the decision-making quantified with AHP provides a good model for mirroring behavior. Nevertheless, this approach may be limited when very simple decisions heuristics are used or stakeholders have to reach decisions under extenuating circumstances.

4.4 Construction sector differences

The main differences between structural (SE) and civil engineering (CE) were found regarding stakeholders' behavior. Generally, the RMCM alternatives were chosen more frequently throughout the construction process in CE than in SE. This confirms the findings from Moser and Bertschinger (2004) and Spoerri et al. (2009) seeing a broader acceptance of RMCM in CE. Public awarding authorities are the exception in SE. They act as role models considering RMCM almost as often as their colleagues in CE. The great behavioral differences between the construction sectors arise from construction experts' recommendations. In CE construction experts frequently recommended RMCM (>40%) whereas in SE RMCM is seldom recommended (<16%) by the experts. Furthermore, the clear differentiation between applications and types of RMCM in CE, demonstrated the knowledge penetration in this sector in contrast to SE, where little differentiation is made.

While behavior strongly differs between the sectors, the influencing criteria are generally the same. However, a slightly higher importance of economic aspects in CE and ecological aspects in SE was observed. This may be explainable by the fact that the economic advantages of RMCM are larger in CE than in SE, due more unbonded applications, onsite recycling and consequently decreasing disposal costs, (Moser et al., 2004).

4.5 Potential of and limitation to the approach

Analytical hierarchy process (AHP): AHP allows one to directly address decision-making. The good alignment of decision-making outcome and behavior demonstrates the potential of the method. In addition, the reasonably low inconsistencies observed confirm the assumption of the approach. However, the pair-wise comparison of criteria and alternatives per criterion requires a lot of effort to filling in the questionnaire. This may have lead to higher drop-out and lower response rates than those achieved in behavioral reporting studies.

Sample: Sustainable construction friendly stakeholders may be slightly overrepresented in the sample, but with little effect on the final behavior regarding the demand for RMCM. The share of awarding authorities specifying sustainable construction in the sample (>50% for SE) is rather high, compared with that in the MINERGIE market, i.e. a share of about 16% in 2008 for new residential buildings (AMI, 2010b, BfS, 2008a). Although the construction stakeholders' general acceptance of sustainable construction is doubtless higher than the share of the major label, the real number may lie between the two. On the other hand, the comparison of the final tender selection decision (i.e. ~90% conventional material in SE) with the 88% found by Moser and Bertschinger (2004) shows the plausibility of the results.

Regional differences: The trend of recycling friendlier behavior found in urban regions accurately reflects experts' experience (Moser et al., 2004). The small sample sizes in the French-speaking part of Switzerland may limit the regional comparative analysis. Therefore, a cautious appraisal of the absence of behavioral and decision-making differences between the linguistic regions is required.

4.6 Policy recommendation

Key policy recommendations emerging from the study are: (i) The information and education of construction experts is clearly the best point of leverage for fostering the demand for RMCM, as already has been proposed by Spoerri et al. (2009). In particular, structural engineers and architects in SE have to be addressed as parties involved in the design process. Engineers, for example, decide to a large extent based on laws and standards when recommending mainly conventional materials in their decisive design specifications. This observation suggests that law (FOEN, 2006) and standards (KBOB, 2007, SIA, 2010, VSS, 1998a) governing the use of RMCM are not yet widely recognized by construction experts, although they recently entered into force. We therefore recommend strengthening efforts to inform stakeholders about the new law and standards in combination with the distribution of reports about reference buildings, aiming to increase engineers' experience with RMCM, which is the second decisive parameter. (ii) The path taken to increase awarding authorities' sustainable construction acceptance via labeling seems to have been successful, as the rates of growth in the number of MINERGIE certificates indicate (AMI, 2010b). An increased use of labels requiring recycling materials could increase the importance of awarding authorities' initial specification on subsequent material decisions. Therefore, we recommend fostering sustainable construction labels which include the use of RMCM if a better incorporation of RMCM in the construction process is desired.

5. Conclusion and outlook

Our analysis of the behavior of construction stakeholders has confirmed that they mainly prefer conventional materials, although this finding differed significantly between construction sectors. Where in civil engineering (CE) RMCM were broadly accepted with more than thirty percent, RMCM were still niche products in structural engineering (SE) with less than ten percent. Furthermore we have shown that the awarding authorities' initial project specification had little relevance to the subsequent material specific decision. It was the engineers' design specifications, mainly influenced by law, standards and experience, which stood at the origin of these material specific decisions. All subsequent decisions in the chain were primarily influenced by the interaction criteria (i.e. recommendation or specification from the previous stakeholder). That is the reason that stakeholders involved later in the chain usually followed the engineers' recommendation. Furthermore construction stakeholders usually decided rationally (i.e. make consistent judgments in the AHP) and behave rationally (i.e. good alignment of decision-making outcome with behavior).

For further research on scenario development about the future demand for RMCM, one promising route might be to model the interaction of construction stakeholders as indicated by the importance of the interaction criteria. In addition, the heterogeneity of the stakeholder groups needs to be addressed, although most of the decision parameters show clear trends.

Stakeholders with completely different decision preferences do exist, making it important to know who is interacting with whom, when and where. A bottom-up simulation method that is able to capture the interaction complexity would be a promising means to assess the sustainability of future RMCM development.

Acknowledgements:

The authors thank all the experts for their support, time and knowledge; Reto Meyer and Irène Barras for their support; Giuseppe Feola for the critical comments; Thomas Ruddy for editing the text; and FEDRO (Swiss Federal Roads Office), FOEN (Federal Office for the Environment), AWEL (Amt für Abfall, Wasser, Energie und Luft; Environmental Agency) of canton Zurich, AHB (Amt für Hochbauten; Office for structural engineering) of the City of Zurich and Eberhard Recycling AG for funding the study as part of a cooperative project with the TSL (Technology and Society Laboratory) at EMPA and the SIE (Social and Industrial Ecology) group at University of Zurich.

References

Aguaron J, Moreno-Jimenez JM. The geometric consistency index: Approximated thresholds. Eur J Oper Res. 2003;147:137-45.

Ajzen I. The theory of planned behavior. Organ Behav Hum Decis Process. 1991;50:179-211.

AMI. MINERGIE; List of Buildings. Association Minergie (AMI); 2010a.

AMI. MINERGIE; Statistics 2009. Association Minergie (AMI); 2010b.

AMI. Reglement zur Nutzung der Qualitätsmarke MINERGIE [Standards for the MINERGIE label usage]. Association Minergie (AMI); 2010c.

Amihud Y, Lev B. Risk reduction as a managerial motive for conglomerate mergers. Bell Journal of Economics. 1981;12:605-17.

Bergsdal H, Brattebo H, Bohne RA, Mueller DB. Dynamic material flow analysis for Norway's dwelling stock. Build Res Informat. 2007;35:557-70.

BfS. Bau- und Wohnbaustatistik [Building and construction statistics]. annually. Neuchâtel: Swiss Federal Statistical Office (BfS); 2008a.

BfS. Haushaltsbudgeterhebung (HABE) [Household budged census]. annually. Neuchâtel: Swiss Federal Statistical Office (BfS); 2008b.

BfS. Schweizerische Arbeitskräfteerhebung (SAKE) [Swiss labour census]. annually. Neuchâtel: Swiss Federal Statistical Office (BfS); 2008c.

BfS. Statistik des jährlichen Bevölkerungsstandes (ESPOP) [Annual population statistics]. annually. Neuchâtel: Swiss Federal Statistical Office (BfS); 2008d.

Blum A, Stutzriemer S. Recycled construction minerals for urban infrastructure in Germany: non-technical issues. 2007;Minerals & Energy:148-58.

Buechi C. "Röstigraben": das Verhältnis zwischen deutscher und französischer Schweiz : Geschichte und Perspektiven [History and perspective of the relation between the French and the German part of Switzerland]. Zürich: NZZ Verlag; 2000.

Busenitz LW, Barney JB. Differences between entrepreneurs and managers in large organizations: Biases and heuristics in strategic decision-making. J Bus Ventur. 1997;12:9-30.

Diekmann A. Empirische Sozialforschung; Grundlagen, Methoden, Anwendungen [Empirical social research. foundations, methods, applications] Reinbek: Rowohlt 2007.

Duran X, Lenihan H, O'Regan B. A model for assessing the economic viability of construction and demolition waste recycling - the case of Ireland. Resour Conserv Recycl. 2006;46:302-20.

EBERHARD. Baustoffe 2010. Oberglatt2010.

Eberhard J, Martin J. Kosten und Nutzen: Wärmeschutz bei Wohnbauten [Costs and Benefits: Insulation in Residential Buildings). Bern: Bundesamt für Energie (BFE); 2003.

Fatta D, Papadopoulos A, Avramikos E, Sgourou E, Moustakas K, Kourmoussis F, et al. Generation and management of construction and demolition waste in Greece - an existing challenge. Resour Conserv Recycl. 2003;40:81-91.

Feola G, Binder C. The integrative agent-centered (IAC) framework as a conceptual tool to investigate transition processes in local agricultural systems. First European Conference on Sustainability Transitions: Dynamics and Governance of Transitions to to Sustainability. Amsterdam, The Netherlands2009.

Finucane ML, Alhakami A, Slovic P, Johnson SM. The affect heuristic in judgments of risks and benefits. J Behav Decis Mak. 2000;13:1-17.

FOEN. Bauabfälle Schweiz - Mengen, Perspektiven und Entsorgungswege. Band 1: Kennwerte [Construction and demolition waste in Switzerland - amounts, perspectives and disposal routes. Volume 1: Statistical values]. Umwelt-Materialien. Bern: Federal Office for the Environment (FOEN); 2001a.

FOEN. Bauabfälle Schweiz - Mengen, Perspektiven und Entsorgungswege. Band 2: Kantonale Werte [Construction and demolition waste in Switzerland - amounts, perspectives and disposal routes. Volume 2: Cantonal values]. Umwelt-Materialien. Bern: Federal Office for the Environment (FOEN); 2001b.

FOEN. An overview on waste amounts and recycling in 2004. Bern: Federal Office for the Environment (FOEN); 2005.

FOEN. Richtlinie für die Verwertung mineralischer Bauabfälle (Ausbauasphalt, Strassenaufbruch, Betonabbruch, Mischabbruch) [Directive for the reuse of mineral construction and demolition waste]. Umwelt Vollzug. Bern: Federal Office for the Environment (FOEN); 2006. p. 34.

Forman EH, Gass SI. The analytic hierarchy process - an exposition. Oper Res. 2001;49:469-86.

Hao JL, Hills MJ, Huang T. A simulation model using system dynamic method for construction and demolition waste management in Hong Kong. Construction Innovation. 2007;7:7-21.

Hashimoto S, Tanikawa H, Moriguchi Y. Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. Waste Management. 2007;27:1725-38.

HASTAG. Products and Prizes 2010. Zürich2010.

Hoffmann C, Jacobs F. Recyclingbeton aus Beton- und Mischabbruchgranulat [Recycling concrete with concrete waste and mixed rubble as aggregates]. Dübendorf: Material Science and Technology (EMPA), Abteilung Beton/Bauchemie und TFB, Technische Forschung und Beratung für Zement und Beton, Wildegg; 2007.

Hofmann W, Patt B. Konstruktionen aus Mischabbruch [Structural concrete with mixed rubble aggregates]. tec21; Die Fachzeitschrift für Architektur, Ingenieurwesen und Umwelt. 2006;10:8-10.

Hotz M-C, Weibel F. Arealstatistik Schweiz [Swiss landuse statistics]. Neuchâtel: Bundesamt für Statistik (BFS); 2005.

Huang WL, Lin DH, Chang NB, Lin KS. Recycling of construction and demolition waste via a mechanical sorting process. Resour Conserv Recycl. 2002;37:23-37.

Jang YC, Townsend T. Sulfate leaching from recovered construction and demolition debris fines. Adv Environ Res. 2001;5:203-17.

Johnson EJ, Payne JW, Bettman JR. Information displays and preference reversals. Organ Behav Hum Decis Process. 1988;42:1-21.

Jungermann H, Pfister H-R, Fischer K. Die Psychologie der Entscheidung: eine Einführung [Decision psychology - an introduction]. Heidelberg: Spektrum Akademischer Verlag; 1998.

Kahneman D. Maps of bounded rationality: Psychology for behavioral economics. Am Econ Rev. 2003;93:1449-75.

Kahneman D, Knetsch JL, Thaler RH. Anomalies - The endowment effect, loss aversion and status-quo bias. J Econ Perspect. 1991;5:193-206.

KBOB. Beton aus recyclierter Gesteinskörnung [Concrete with recycled aggregates]. Bern: Koordination der Bau und Liegenschaftsorgane des Bundes (KBOB); 2007. p. 6.

Knoeri C, Binder C, Althaus HJ. An Agent Operationalization Approach for Agent-based Modeling. submitted. 2010.

Lawson N, Douglas I, Garvin S, McGrath C, Manning D, Jonathan V. Recycling construction and demolition wastes - a UK perspective. Environmental Management and Health. 2001;12:146 - 57

Li X. Recycling and reuse of waste concrete in China: Part I. Material behavior of recycled aggregate concrete. Resources, Conservation and Recycling. 2008;53:36-44.

Loughlin DH, Barlaz MA. Policies for Strengthening Markets for Recyclables: A Worldwide Perspective. Critical Reviews in Environmental Science and Technology. 2006;36.

Mendoza GA, Martins H. Multi-criteria decision analysis in natural resource management: A critical review of methods and new modeling paradigms. Forest Ecology and Management. 2006;230:1-22.

Mieg HA, Näf M. Experteninterviews in den Umwelt- und Planungswissenschaften [Expert interviews in environmental and management research]. Lengerich: Pabst Science Publishers; 2006.

Moser K, Bertschinger H, Hugener M, Richner P, Richter K. Baustoffmanagement 21 an der EMPA, Stand des Wissens und Forschungsbedarf [Management of construction materials at EMPA: standard of knowledge and need for further research]. Material Science and Technology (EMPA); 2004.

Muller DB. Stock dynamics for forecasting material flows - Case study for housing in The Netherlands. Ecol Econ. 2006;59:142-56.

Pettigrew AM. The Politics of Organizational decision-making. London: Tavistock; 1973.

Poon C-S, Kou S-c, Wan H-w, Etxeberria M. Properties of concrete blocks prepared with low grade recycled aggregates. Waste Management. 2009;29:2369-77.

Rao A, Jha KN, Misra S. Use of aggregates from recycled construction and demolition waste in concrete. Resources, Conservation and Recycling. 2007;50:71-81.

Robinson GR, Menzie WD, Hyun H. Recycling of construction debris as aggregate in the Mid-Atlantic Region, USA. Resour Conserv Recycl. 2004;42:275-94.

Saaty TL. The analytical hierarchy process: planning, priority setting, resource allocation. New York: McGraw-Hill; 1980.

Saaty TL. How to Make a Decision - the Analytic Hierarchy Process. Eur J Oper Res. 1990;48:9-26.

Schachermayer E, Lahner T, Brunner PH. Assessment of two different separation techniques for building wastes. Waste Manage Res. 2000;18:16-24.

Schwenk CR. COGNITIVE SIMPLIFICATION PROCESSES IN STRATEGIC DECISION-MAKING. Strateg Manage J. 1984;5:111-28.

SIA. Recyclingbeton [Recycling Concrete]. 2 ed: Schweizerischer Ingenieur und Architekten Verein (SIA), Schweizer Norm (SN); 2010.

Simon HA. A behavioral model of rational choice. Q J Econ. 1955;69:99-118.

Simon HA. Information-processiong models of cognition. Annu Rev Psychol. 1979;30:363-96.

Spoerri A, Lang DJ, Binder CR, Scholz RW. Expert-based scenarios for strategic waste and resource management planning - C&D waste recycling in the Canton of Zurich, Switzerland. Resources, Conservation and Recycling. 2009;53:592-600.

Staeubli B, Wymann A, Morf L, Bosshard F. Abfall im Kanton Zürich [Waste in the Canton of Zurich]. statistikinfo. Zürich: Statistisches Amt des Kanton Zürich; 2005.

Susskind L, McKearnnan S, Thomas-Larmer J. The consensus building handbook - a comprehensive guide to reach agreement. Thousand Oaks, CA: Sage; 1999.

Svenson O. Process Descriptions of Decision-Making. Organizational Behavior and Human Performance. 1979;23:86-112.

Svenson O. Decision making and the search for fundamental psychological regularities: What can be learned from a process perspective? Organ Behav Hum Decis Process. 1996;65:252-67.

Triandis HC. Values, Attitudes and Interpersonal Behavior, Nebraska Symposium on Motivation. Lincoln/London: University of Nebraska Press; 1980.

Uebersax H. Kies für Generationen: Kommunikation [Gravel for Generations: Communication]. Zürich: Amt für Abfall, Wasser, Energie und Luft des Kanton Zürich; Abt. Abfall; 2005.

VSS. Recycling; Allgemeines [General recycling]. Vereinigung-Schweizerischer-Strassenfachleute, (VSS), Schweizer-Norm, (SN); 1998a.

VSS. Recycling; Ausbauasphalt [Asphalt recycling]. Vereinigung-Schweizerischer-Strassenfachleute (VSS), Schweizer Norm (SN); 1998b.

VSS. Recycling; Betonabbruch [Concrete rubble recycling]. Vereinigung-Schweizerischer-Strassenfachleute (VSS), Schweizer Norm (SN); 1998c.

VSS. Recycling; Mischabbruch [Mixed rubble recycling]. Vereinigung-Schweizerischer-Strassenfachleute (VSS), Schweizer Norm (SN); 1998d.

VSS. Recycling; Strassenaufbruch [Road demolition debris recycling]. Vereinigung-Schweizerischer-Strassenfachleute (VSS), Schweiizer Norm (SN); 1998e.

Weil M, Jeske U, Schebek L. Closed-loop recycling of construction and demolition waste in Germany in view of stricter environmental threshold values. Waste Manage Res. 2006;24:197-206.

Witt U. ''Lock-in'' vs. ''critical masses'' - industrial change under network externalities. Int J Ind Organ. 1997;15:753-73.

Appendix A: Sample description

Table A.1: Sample description structural engineering

Stakeholder group			Private awarding authorities N (50)		Public awarding authorities N (35)		Commercial awarding authorities N (41)		Architects N (54)		Engineers N (70)		Contractors N (49)		ZH, BE, VD, GE	Swiss	ZH, BE, VD, GE / Swiss
	Variable	labels [unit]	f_o	f_e	f_o	f_e	f_o	f_e	f_o		f_o		f_o		f_o	f_o	Sources
socio-demographic data	Age	25-29 years [%]	**0.0%**		**0.0%**		**0.0%**		**0.0%**		**4.4%**		2.2%		10.77%	9.86%	
		30-34 years [%]	**2.2%**		**3.0%**		**2.8%**		**0.0%**		**11.1%**		4.4%		11.56%	10.44%	
		35-39 years [%]	**11.1%**		**6.1%**		**2.8%**		**13.3%**		**13.3%**		17.8%		12.87%	11.95%	
		40-44 years [%]	**17.8%**		**12.1%**		**22.2%**		**17.8%**		**4.4%**		13.3%		13.87%	13.18%	
		45-49 years [%]	**15.6%**		**12.1%**		**8.3%**		**15.6%**		**15.6%**		22.2%		12.52%	12.08%	
		50-54 years [%]	**22.2%**		**21.2%**		**16.7%**		**20.0%**		**13.3%**		13.3%		10.96%	10.57%	BfS (2008). Statistik des jährlichen Bevölkerungsstandes (ESPOP). Jährlich.
		55-59 years [%]	**6.7%**		**24.2%**		**16.7%**		**8.9%**		**13.3%**		11.1%		10.22%	9.71%	
		60-64 years [%]	**6.7%**		**21.2%**		**19.4%**		**20.0%**		**13.3%**		8.9%		9.74%	9.08%	
		65-69 years [%]	**13.3%**		**0.0%**		**8.3%**		**4.4%**		**11.1%**		4.4%		7.49%	7.15%	
		70-74 years [%]	**4.4%**		**0.0%**		**2.8%**		**0.0%**		**0.0%**		4.4%		6.21%	5.97%	
	Gender	male [%]	**83%**		**91%**		**98%**		**96%**		**99%**		**98%**		49%	49%	
		female [%]	**17%**		**9%**		**2%**		**4%**		**1%**		**2%**		51%	51%	
	Education	Obligatory school [%]	**4%**		**0%**		**0%**		**0%**		**0%**		**0%**		18%	13%	
		Secondary degree [%]	**50%**		**69%**		**45%**		**24%**		**4%**		**57%**		48%	64%	BfS (2008). Schweizerische Arbeitskräfteerhebung (SAKE). Jährlich.
		Tertiary degree [%]	**42%**		**29%**		**48%**		**59%**		**93%**		**39%**		24%	23%	
		no answer [%]	**4%**		**3%**		**8%**		**17%**		**3%**		**4%**		7%	0%	
	Income	< 50'000 CHF [%]	**4%**		**3%**		**2%**		**0%**		**1%**		**0%**		16%		
		50'000 - 99'999 CHF [%]	**18%**		**20%**		**20%**		**25%**		**19%**		**31%**		29%		BfS (2008). Schweizerische Arbeitskräfteerhebung (SAKE). Jährlich. BfS (2008). Haushaltsbudgeterhebung (HABE). Jährlich.
		100'000 - 149'999 CHF [%]	**26%**		**46%**		**33%**		**29%**		**34%**		**22%**		21%		
		> 150'000 CHF [%]	**38%**		**17%**		**25%**		**13%**		**31%**		**29%**		24%		
		no answer [%]	**14%**		**14%**		**25%**		**33%**		**14%**		**18%**		11%		
spatial data	Canton	Zürich [%]	34%	34%	55%	41%	**49%**	45%	20%		47%		47%		41%	18%	
		Bern [%]	36%	25%	23%	26%	**41%**	26%	35%		26%		35%		26%	11%	
		Vaud [%]	18%	27%	11%	16%	**5%**	14%	17%		18%		6%		18%	8%	
		Gèneve [%]	12%	15%	11%	17%	**5%**	14%	28%		9%		12%		15%	6%	BfS (2008). Bau- und Wohnbaustatistik. Jährlich.
	Rural - urban distribution	Central urban community [%]	16%	14%	**14%**	53%	41%	43%	39%		**54%**		25%		36%	31%	
		Agglomeration community [%]	58%	57%	**49%**	36%	36%	44%	44%		**29%**		48%		47%	43%	
		Rural community [%]	26%	29%	**37%**	11%	22%	13%	17%		**17%**		27%		17%	26%	
construction data	Type of construction	New construction [%]	72%	64%	29%	31%	66%	69%	67%		*91%*		71%		61%	65%	
		Refurbishing [%]	28%	36%	71%	69%	34%	31%	33%		*9%*		29%		39%	35%	
	Building category	single-family house [%]	60%		3%		5%		35%		16%		**29%**				
		apartment house [%]	24%	94%	3%	9%	49%	58%	19%		39%		**45%**		56.25%	62.98%	BfS (2008). Bau- und Wohnbaustatistik. Jährlich.
		dwelling with secondary function [%]	4%		3%		12%		15%		15%		**10%**				
		building with minor residential function [%]	2%		14%		10%		7%		6%		**4%**				
		non-residential building [%]	10%	6%	71%	78%	24%	40%	24%		19%		**12%**		40.38%	33.92%	
		temporary building [%]	0%		6%		0%		0%		1%		**0%**				
		others [%]	0%	0%	0%	13%	0%	2%	0%		4%		**0%**		3.37%	3.09%	
	Building sum (contractors: contract sum)	<100'000 CHF *(<50'000 CHF)* [%]	4%		6%		0%		0%		0%		(4%)				
		100'000-499'999 CHF *(50'000-99'999 CHF)* [%]	26%		17%		5%		7%		7%		(8%)				
		500'000-999'999 CHF *(100'000 - 149'000 CHF)* [%]	37%		8%		10%		24%		9%		(33%)				
		>1'000'000 CHF *(>150'000 CHF)* [%]	31%		66%		85%		69%		80%		(53%)				
		no answer [%]	2%		3%		0%		0%		4%		(2%)				
	Building radius	25% quantile [km]		0.0		0.0		0.3		3.0		4.0		4.0			
		Median [km]	50	0.3	34 [ii]	0.3	41	0.5	53	5.0	70	10.0	49	10.0			
		75% quantile [km]		3.0		3.0		1.0		18.0		25.0		15.0			
	Construction frequency	25% quantile [number of projects / year]		0.2		0.8		0.4		3.5		8.0		5.3			
		Median [number of projects / year]	50 [i]	0.2	30	2.7	40	0.8	53	5.0	67	15.0	48	12.5			
		75% quantile [number of projects / year]		0.2		11.8		3.0		10.0		35.0		20.0			

Bold numbers indicate significant differences (Chi-Square < 0.05) from f_o (observed frequencies in the samples) to f_e (expected frequencies equal to the observed frequencies in the investigation area (ZH, BE, VD, GE) or the frequencies of investment per stakeholder group where specified).
[i] 78% (1 in the last 5 years), [ii] excluding one outlier at 300 km

Table A.2: Sample description civil engineering

	Stakeholder group			Public awarding authorities	Engineers	Contractors	ZH, BE, VD, GE	Swiss	ZH, BE, VD, GE / Swiss
				N (50)	N (42)	N (23)			
	Variable	labels [unit]		f_o	f_o	f_o	$f_o = f_e$ (Sample)	f_o	Sources
sociographic data	**Age**	25-29 years [%]		**0.0%**	4.9%	0.0%	10.77%	9.86%	BfS (2008). Statistik des jährlichen Bevölkerungsstandes (ESPOP). Jährlich.
		30-34 years [%]		**2.1%**	2.4%	8.7%	11.56%	10.44%	
		35-39 years [%]		**19.1%**	9.8%	4.3%	12.87%	11.95%	
		40-44 years [%]		**12.8%**	9.8%	13.0%	13.87%	13.18%	
		45-49 years [%]		**8.5%**	14.6%	13.0%	12.52%	12.08%	
		50-54 years [%]		**10.6%**	22.0%	17.4%	10.96%	10.57%	
		55-59 years [%]		**29.8%**	17.1%	13.0%	10.22%	9.71%	
		60-64 years [%]		**17.0%**	9.8%	21.7%	9.74%	9.08%	
		65-69 years [%]		**0.0%**	9.8%	4.3%	7.49%	7.15%	
		70-74 years [%]		**0.0%**	0.0%	4.3%	6.21%	5.97%	
	Gender	male [%]		**94%**	**98%**	**96%**	49%	49%	
		female [%]		**6%**	**2%**	**4%**	51%	51%	
	Education	Obligatory school [%]		**0%**	**0%**	**0%**	18%	13%	BfS (2008). Schweizerische Arbeitskräfteerhebung (SAKE). Jährlich.
		Secondary degree [%]		**52%**	**12%**	**48%**	48%	64%	
		Tertiary degree [%]		**42%**	**83%**	**52%**	24%	23%	
		no answer [%]		**6%**	**5%**	**0%**	7%	0%	
	Income	< 50'000 CHF [%]		**0%**	**0%**	**0%**	16%		BfS (2008). Schweizerische Arbeitskräfteerhebung (SAKE). Jährlich. BfS (2008). Haushaltsbudgeterhebung (HABE). Jährlich.
		50'000 - 99'999 CHF [%]		**16%**	**19%**	**13%**	29%		
		100'000 - 149'999 CHF [%]		**54%**	**26%**	**26%**	21%		
		> 150'000 CHF [%]		**8%**	**31%**	**44%**	24%		
		no answer [%]		**22%**	**24%**	**17%**	11%		
spatial data	**Canton**	Zürich [%]		**38%**	**31%**	**44%**	41%	14%	BfS (2008). Bau- und Wohnbaustatistik. Jährlich.
		Bern [%]		**46%**	**36%**	**57%**	26%	11%	
		Vaud [%]		**12%**	**31%**	**0%**	18%	7%	
		Gèneve [%]		**4%**	**2%**	**0%**	15%	4%	
	Rural - urban distribution	Central urban community [%]		**28%**	45%	**30%**	46%	37%	
		Agglomeration community [%]		**46%**	31%	**35%**	40%	34%	
		Rural community [%]		**26%**	24%	**35%**	14%	29%	
construction related data	**Type of construction**	New construction [%]		44%	45%	65%	45%	46%	BfS (2008). Bau- und Wohnbaustatistik. Jährlich.
		Refurbishing [%]		56%	55%	35%	55%	54%	
	Building category (multiple answers possible)	Road construction	community road [%]	**38%**	**32%**	**31%**	63.33%	60.42%	Schneider, M. and Rubli, S. (2008). Resourcenmodell mineralischer Baustoffe der Schweiz.
			cantonal road [%]	**9%**	**9%**	**17%**			
			national road [%]	**1%**	**6%**	**0%**			
		Railruad construction		**1%**	**6%**	**0%**	7.01%	6.72%	
		Water supply and sewerage [%]		**30%**	**17%**	**25%**	20.40%	18.97%	
		Energy supply [%]		**11%**	**16%**	**11%**	3.74%	3.19%	
		Civil engineering structures	Bridge [%]	**6%**	**7%**	**11%**	5.52%	10.71%	
			Tunnel [%]	**0%**	**1%**	**0%**			
			Underpass / overbridge [%]	**1%**	**3%**	**0%**			
		others [%]		**3%**	**3%**	**6%**			
	Building sum (contractors: contract sum)	<100'000 CHF (<50'000 CHF) [%]		8%	0%	(0%)			
		100'000-499'999 CHF (50'000-99'999 CHF) [%]		24%	10%	(9%)			
		500'000-999'999 CHF (100'000 - 499'000 CHF) [%]		16%	21%	(21%)			
		>1'000'000 CHF (>500'000 CHF) [%]		52%	64%	(70%)			
		no answer [%]		0%	5%	(0%)			
	Building radius	25% quantile [km]		0.5	2.5	2.0			
		Median [km]		1.0	10.0	8.0			
		75% quantile [km]		3.3	20.0	23.8			
	Construction frequency	25% quantile [number of projects / year]		1.0	3.3	8.0			
		Median [number of projects / year]		2.0	10.0	12.0			
		75% quantile [number of projects / year]		6.0	15.0	15.0			

Bold numbers indicate significant differences (Chi-Square < 0.05) from f_o (observed frequencies in the samples) to f_e (expected frequencies equal to the observed frequencies in the investigation area (ZH, BE, VD, GE).

Appendix B: Decision criteria description

Table B.1: Stakeholders' decision criteria in SE ([1] private, [2] commercial, [3] public indicate criteria and descriptive properties appearing only for the particular awarding authority group. Sustainable construction (SC); Decision criteria are listed and described according to the chronological decision interaction.)

stakeholder	decision	decision criteria	description
awarding authorities	*project specification (1)*	• social aspects	trends, image, social desirability [1,3], political objectives [3] regarding SC and RMCM
		• economic aspects	expected investment and operation costs and allocated budget for SC and RMCM
		• ecological aspects	knowledge and expectations about the ecological performance of SC and RMCM
structural engineers	design specification (2)	• *project specification*	project specification from the awarding authorities about SC or RMCM
	(engineers' recommendation)	• expected costs	expected tender price of RMCM and conventional materials
		• experience	experience with conventional materials and RMCM
		• laws and standards	existence of laws and standards regarding the usage of RMCM
architects	project design (3)	• *project specification*	project specification from the awarding authorities about SC or RMCM
	(project recommendation)	• expected costs	expected tender price of RMCM and conventional materials
		• *engineers' recommendation*	recommendation of the engineers regarding the usage of RMCM
		• image	personal image of RMCM
		• aesthetical aspects	aesthetical performance of RMCM
awarding authorities	project confirmation (4)	• *project recommendation*	project recommendation of the architects regarding the usage of RMCM
	(basis for the tender documents)	• expected costs	expected tender price of RMCM and conventional materials
		• technical aspects [1,2]	knowledge and expectations about the technical performance of RMCM [1,2]
		• ecological aspects [1]	knowledge and expectations about the ecological performance of RMCM [1]
		• image [2,3]	personal image of RMCM [2,3]
		• marketability [2]	assessed marketability of buildings with RMCM [2]
		• political aspects [3]	political objectives regarding the usage of RMCM [3]
contractors	tender (5)	• *tender documents*	material specifications in the tender documents
	(leading to a submitted tender price)	• economic aspects	raw material price and availability of conventional materials and RMCM, share of the material price on the overall tender sum
		• experience	experience with conventional materials and RMCM
		• technical aspects	technical feasibility and quality of RMCM, existence of laws and standards regarding the usage of RMCM, risk assessment and liability issues

stakeholder	decision	• decision criteria	description
awarding authorities	tender selection (6)	• *tender documents*	materials specified in the tender documents[1,2]
		• tender price	tender price of tenders with conventional materials and RMCM
		• technical aspects	knowledge and expectations about the technical performance of RMCM [1,2]
		• ecological aspects	knowledge and expectations about the ecological performance of RMCM [1] ,transport distances [3], ecological management of the company [3]
		• marketability [1]	assessed marketability of buildings with RMCM [2]
		• quality management [3]	quality management of the company [3]
		• company references [3]	references and experience of the company with the particular type of project [3]
		• staff references [3]	knowledge, references and experience of the staff with the particular type of project [3]
		• education [3]	apprenticeship position offers [3]

Table B.2: Stakeholders' decision criteria in CE (Sustainable construction (SC); Decision criteria are listed and described according to the chronological decision interaction.)

stakeholder	decision	decision criteria	description
awarding authorities	*project specification (1)*	• social aspects	trends, image and social desirability, political objectives regarding SC and RMCM
		• economic aspects	expected investment and operation costs SC and RMCM, demolition and disposal costs in the project
		• ecological aspects	knowledge and expectations about the ecological performance of SC and RMCM
		• technical aspects	knowledge and expectations about the technical performance of SC and RMCM
civil engineers	project design (2) *(project recommendation)*	• *project specification*	project specification from the awarding authorities about SC or RMCM
		• expected costs	expected tender price of RMCM and conventional materials, demolition and disposal costs in the project
		• experience	experience with conventional materials and RMCM
		• laws and standards	existence of laws and standards regarding the usage of RMCM
awarding authorities	project confirmation (3) *(basis for the tender documents)*	• *project recommendation*	project recommendation of the engineers regarding the usage of RMCM
		• expected costs	expected tender price of RMCM and conventional materials
		• political aspects	political objectives regarding the usage of RMCM
		• image	personal image of RMCM
contractors	tender (4) *(leading to a submitted tender price)*	• selection criteria	predefined tender selection criteria from the awarding authorities
		• economic aspects	raw material price and availability of conventional materials and RMCM, demolition and disposal costs in the project
		• experience	experience with conventional materials and RMCM
		• technical aspects	technical feasibility and quality of RMCM, existence of laws and standards regarding the usage of RMCM, risk assessment and liability issues
		• *tender documents*	material specifications in the tender documents
awarding authorities	tender selection (5)	• *tender price*	tender price of tenders with conventional materials and RMCM
		• quality management	quality management of the company
		• company references	references and experience of the company with the particular type of project
		• staff references	knowledge, references and experience of the staff with the particular type of project
		• education	apprenticeship position offers
		• ecological aspects	transport distances, ecological management of the company

Publication III

Enhancing recycling of construction materials: an agent-based model with empirically based decision parameters

Overview

This paper exemplifies how environmental innovations in complex socio-technical systems could be captured with empirically based ABM with the case study of Swiss construction actors` decisions towards recycling. Construction stakeholders' interaction and decisions, beforehand empirically operationalized with the agent operationalization approach, were implemented aiming at a realistic representation of demand for construction materials. Key factors affecting the demand were analysed and scenarios for aligning potential supply and demand developed. This example demonstrates the value of empirically operationalized agent architectures on one hand, but also highlights the importance of an iterative model development.

Main findings

- *Realistic demand representation:* Most realistic demand representation was reached when option awareness was included in addition to the actual empirical based multi-criteria decision represented as discrete choices.

- *Key factors affecting the demand:* The fraction of recycling materials applied was most sensitive to stakeholders` awareness of such materials as an option. In particular the architects and engineers reaction to previous decisions in the agent interaction chain was a key factor. Further, the demand showed price elasticity only in a particular range around current prices, as a matter of fact of construction stakeholders' multi criteria decisions.

- *Policy recommendations:* The most effective interventions for a transition towards a closed-loop recycling are extensive information campaigns combined with small economic incentives leading up to 70% demand for RC of all demand for concrete. However, a complete reuse, in particular of the large amounts of mixed rubble, might require higher aggregates substitution rates as the current 40%, or further making RC to the mainstream type of concrete applied.

Relevance for the doctoral thesis

This study contributed to the thesis in three ways; (i) by exemplifying the application of the agent operationalization approach developed, (ii) analysing the key factor affecting the demand for RMCM, and (iii) modelling the supply and demand related to different scenarios relevant for the synthesis.

Enhancing recycling of construction materials: an agent-based model with empirically based decision parameters

Christof Knoeri [1,3], Igor Nikolic [2], Hans-Joerg Althaus [3], Claudia R. Binder [4]

[1] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT UK

[2] Section Energy & Industry, Faculty of Technology, Policy and Management, Delft University of Technology, The Netherlands

[3] Laboratory for Technology and Society, Empa, Swiss Federal Laboratories for Materials Science and Technology, Duebendorf, Switzerland

[4] Human Environment Relations, Department of Geography, University of Munich, Germany

Journal of Artificial Societies and Social Simulation (JASSS)

Received: October 2012 Accepted: February 2014 Published: 30th June 2014

Abstract

Recycling of construction material is a valuable option for minimizing construction & demolition waste streams to landfills and mitigating primary mineral resource depletion. Material flows in the construction sector are governed by a complex socio-technical system in which awarding authorities decide in interaction with other actors on the use of construction materials. Currently, construction & demolition waste is still mainly deposited in landfills, as construction actors lack the necessary information and training regarding the use of recycled materials, and as a result have low levels of acceptance for them. This paper presents an agent-based model of the Swiss recycled construction material market based on empirical data derived from the agent operationalization approach. It elaborates on how recycling of construction materials can be enhanced by analysing key factors affecting the demand for recycled construction materials and developing scenarios towards a sustainable construction waste management. Doing so it demonstrates how detailed empirical agent decision data were incrementally included in the ABM model. Raising construction actors' awareness of recycled materials as a decision option, in combination with small price incentives was most effective for enhancing the use of recycled materials. This could lead to a 50% reduction of construction & demolition waste streams to landfills, and significantly reduce the environmental impacts related to concrete applications. From a methodological perspective, although the agent operationalization approach provides a large empirical foundation, incremental model development turned out to be particularly important for the traceability of results and a realistic system representation.

Keywords: Empirical based modelling, socio-technical system, sustainable resource management, multi criteria decision-making, agent operationalization approach, agent-based modelling

1. Introduction

Construction & demolition waste, already being the largest waste fraction by mass (up to 50%) in industrialised countries, is expected to further increase in the future (Schachermayer et al. 2000). Recycling mineral construction materials has been seen as a valuable option, not only for minimising construction & demolition waste streams to landfills, but also for mitigating primary mineral resource depletion (Bergsdal et al. 2007; Hashimoto et al. 2007). In addition, there is potential for mitigating the environmental impacts along the life-cycle of mineral construction materials (Knoeri et al. 2013; Marinkovic et al. 2010). However, due to a lack of construction actors` acceptance of recycled materials, information and training (Knoeri et al. 2011b; Spoerri et al. 2009), recycled mineral construction materials are still deposited or down-cycled (Moser et al. 2004; Tam & Tam 2006), even though technical approval and standards for higher-grade applications exist (Hoffmann & Leemann 2006; SIA 2010). Thus a transition from material through-put to closed-loop recycling is required in construction materials management (Weil et al. 2006).

Material flows in the construction sector are steered by a complex socio-technical system in which awarding authorities decide through interaction with other actors such as engineers, architects and contractors (Knoeri et al. 2011a) on the use - and thereby on the demand - of construction materials. In the Swiss case study heterogeneous construction actors take multi criteria decisions, assigning high weights to the interaction criterion (i.e. specification and recommendations from other actors). Furthermore they select each other for project collaboration based on personal contact, references, reputation and economic factors (Knoeri, et al. 2011b). In contrast to these findings, previous studies modelling actor behaviour in the construction sector have been mainly end-user centred and rarely include system designers and sellers, installers and fitters of certain technological option as autonomous agents (Sopha et al. 2011). Thus the effect of interacting actors on the adaptation of a particular material or technology option is yet unclear.

Agent-based modelling (ABM) is increasingly becoming a standard tool for analysing and modelling transitions in complex socio-ecological (Grimm & Railsback 2005; Janssen & Ostrom 2005) and socio-technical systems (Bergman et al. 2008; Chappin & Dijkema 2010; Haxeltine et al. 2008; Schwarz & Ernst 2009). This is due to ABMs` ability to capture the effects of the interactions between heterogeneous individuals and networks on the system (Garcia 2005; Rahmandad & Sterman 2008). Most of the previous ABM studies analysing socio-technical system transitions are energy focussed. They study either consumer goods such as lighting (Axtell et al. 2001), or household energy generation and transformation such as photovoltaic systems (Ramanath & Gilbert 2004), domestic micro-cogeneration (Polhill et al. 2008), heating systems (Svenson 1990), bio-electricity (Davis et al. 2010), and occupancy behaviour (Andrews et al. 2011). Just recently, ABM has started to be used to explicitly address sustainable material flow management, (e.g. Bollinger at al. (2011)) and showed its potential to enhance the understanding of drivers behind material flows and recycling schemes. Despite this large potential of ABM, its' effectiveness in solving problems more relevant to the real world (Louie &

Carley 2008; Parker et al. 2003) and its empirical foundation has been questioned (Janssen & Ostrom 2006).

This paper presents an agent-based model of Swiss construction actor's decisions and interactions on the use of recycled materials. It aims to elaborate on how recycling of construction materials can be enhanced by analysing key factors affecting the demand for construction materials and developing scenarios leading to a maximal reuse of construction & demolition waste streams. Doing so it demonstrates how the empirical data on construction stakeholder decisions presented in Knoeri et al. (2011b), which were derived through the agent operationalization approach proposed in Knoeri et al. (2011a), can be incrementally included in the model development. The materials and methods section outlines the procedure of incrementally including empirical agent data in the model development and fully specifies the final model. Subsequently the results from the model simulations are presented and discussed, and synthesised in a final conclusion.

2. Materials and methods

2.1 Model development

2.1.1 Empirical agent operationalization

Two general procedures for the model development in the case study were discussed: (i) match observed system level demand patterns of recycled materials with theoretical based agent decisions, or (ii) empirically determine the decision-making of construction agents and implement the observed decision traits. On the system level the only accurate demand data point was a simple recycling rate, while estimates of its historical development and spatial pattern where rather vague (Moser, et al. 2004). Therefore empirically basing the model on agents' decision-making and behaviour was the more promising way forward. The agent operationalization approach provides a step-wise procedure to empirically select the relevant agents affecting the problem addressed, determine their interactions, analyse their decision-making process including its determinants, and test how consistent decision preferences (intention) and behaviour are (Knoeri, et al. 2011a). A detailed empirical analysis of construction actors' interaction, behaviour and decision-making processes is presented in Knoeri et al. (2011b).

2.1.2 Concepts and traits included throughout the model development

Having extensive empirical data about agents` decision-making processes, and behaviour at hand, raises the question of what level of detail of this data should be implemented in an agent-based model. For example, one could simply implement the probabilistic behaviour of agents or their multi-criteria decision-making leading to that behaviour. Therefore we analysed at which level of detail agents' decision-making traits lead to a realistic demand representation at the system level. Besides the agents' decisions traits other concepts such as, how agents select each other, how they learn, as well as how the technical environment is represented might influence a realistic demand representation. Therefore, we elaborate on the inclusion of empirical based decision parameters in view of these other aspects of model development.

Following the model development cycle (e.g. Grimm & Railsback (2005), and Sargent (2008)) we iteratively added or changed the decision traits in the model until a sufficiently accurate representation of the about 11% demand for recycling materials reported (FOEN 2001, 2008; Moser, et al. 2004) was reached. We used model complexity and data requirements as general guidelines for this development. Doing so, we went from simple to more complex decision traits (e.g. probabilistic to multi-criteria decisions) and design concepts (e.g. few to many agents and proxy to explicit material flows). With each model version 100 simulation experiments over the interval of 2010-2050 were run, and the distributions of the average fraction of recycling materials applied was recorded.

Table 1: Concepts and decision traits included in different model versions and development phases, and fraction of recycled concrete applied as main output measure (cf. SI Figure 10)

concepts & traits	phase	I						II						III				
	version	1.0	1.1	1.2	1.3	1.4	1.5	2.0	2.1	2.2	2.3	2.4	2.5	3.0	3.1	3.2	3.3	3.4
agent number & type	small (120)	✓	✓	✓	✓	✓	✓											
	large (5877)							✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	AA separation							✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	reference group size							✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
decision traits	random	✓																
	empirically based		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	fuzzy	✓	✓	✓		✓												
	discrete				✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	multi-criteria										✓	✓	✓	✓	✓	✓	✓	✓
option availability	AA options awareness								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	react to prev. decisions								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	tender if available																✓	✓
	limited link of sustainable constr. with RC																	✓
agent interaction	interaction criteria weights: random	✓	✓															
	interaction criteria weights: empirical based			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	tender based contractor selection									✓	✓	✓	✓	✓	✓	✓	✓	✓
	reference & contact based architect & engineer selection												✓	✓	✓	✓	✓	✓
experience parameter update												✓	✓	✓	✓	✓	✓	✓
economic criteria` price sensitive														✓	✓	✓	✓	✓
image trend sensitive															✓	✓	✓	✓
material availability	unrestricted	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓			
	limited					✓	✓									✓	✓	✓
AA construction probability driven		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
construction investment driven														✓	✓	✓	✓	✓
output measure	project decision	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
	explicit material flows														✓	✓	✓	✓
fraction of recycled concrete applied	mean [%]	**50**	**22**	**42**	**36**	**16**	**16**	**36**	**15**	**19**	**28**	**38**	**42**	**43**	**41**	**43**	**29**	**13**
	StD [%]	4.7	1.8	1.6	16	0.1	1.0	8.6	3.4	4.5	5.2	6.4	5.2	2.9	3.9	3.1	4.0	2.7

Table 1 shows the concepts and decision traits included in the three model development phases: The *first phase* aimed at representing the construction actors' interaction with a limited number of agents with simple probabilistic two-criterion decisions. In this phase the impact of basic concepts such as fuzzy or discrete decisions, random or empirical based decisions and interaction, and limited material availability were tested. The *second phase* focused on a more realistic agent behaviour representation through introducing larger agent numbers, multi-criteria decisions and limited option availabilities related to the agent interaction, according to the empirical findings. The agent interaction was further improved with tender- and experience-based agent selection. The *third and final phase* aimed at a better representation of the case study's systemic properties. Doing so, construction investments were introduced as the model driver and material flows were explicitly modelled in contrast to the first two phases where project decisions were taken as a proxy for the materials applied. This allowed not only a limiting of the availability of recycling materials according to the expected supply of construction waste aggregates, but also a tendering process that is dependent on actual materials available. Additionally, different reactions of construction experts to recommendations were allowed (i.e. consider recycling concrete as option or not if sustainable construction was specified), and specific criteria values such as image and expected prices were updated according to trend and market price.

2.1.3 Lessons learned in the model development

Phase I revealed three lessons learned guiding the subsequent development phases. *(i) Output measure:* Starting with random decisions allowed us to observe and limit potential modelling artefacts. The expected random outcome for the fraction of recycled concrete applied was a first test of the model's structural validity. Since spatial demand patterns emerged already from these simple local interactions (SI Figure 9) we consequently focused on the recycling fraction as an output measure rather than on spatial patterns. *(ii) Fuzzy vs. discrete decisions:* The multi-criteria decision analysis method analytical hierarchy process (AHP) used in this study delivers a normalized vector containing the final options' rating (Saaty 1980). While the mathematical calculation leading to that final rating leaves little room for interpretation, how people interpret and communicate their rating does. We tested two possible interpretations; fuzzy decision where the full ranking is communicated and discrete decisions where only the best performing option is communicated. Fuzzy decisions blurred the decision outcomes in single projects and converged towards the mean of the final decision on the system level. Discrete decisions on the other hand were precise in the individual projects but their outcome varies much more on the system level. Since recommendation and specifications in the construction sector have been found to be rather explicit (Knoeri, et al. 2011b; Ling 2002) we continued with discrete decisions. *(iii) Limiting the material availability* completely dominated the output independently of the decision traits implemented (cf. version 1.4 and 1.5). Analysing the impact of different decision implementations on limiting material availability was thus postponed to the third development phase, where real material flows were considered.

Phase II unveiled the impact of scale, option awareness, and inclusion of more empirical data. *(i) Increasing agent numbers and scale* reduced the outcome variability, limiting the effect of a single agent (cf. version 1.3 vs. 2.0). Due to runtime restrictions, but also because sufficient accuracy was reached, the model to reality relation was kept as 1:100. Bollinger et al. (2011) demonstrated a 1 to 1 representation by modelling the metal fate in mobile phones. What additional insights such 1 to 1 representation capturing every single project in this case might provide and how they relate to the additional simulation and data analysis effort is open for future research. *(ii) Option awareness:* Up to model version 2.0, each decision assumed that besides the conventional materials the recycled option was a known option. This is, at least for the case study, considered far from reality (Spoerri, et al. 2009). Awarding authorities for example only consider sustainable construction as an option at the beginning of the construction process in about 50% of cases (Knoeri, et al. 2011b). Thus from model versions 2.1 onwards the availability of the recycling decision option was limited based on personal awareness. This turned out to be the key step in the model development, since for the first time a somewhat realistic demand for recycling materials emerged. *(iii) Empirical based decisions:* throughout phase 2 better decision data (i.e. multi-criteria decision data), and more of the insight regarding agent interaction (e.g. contractor, architect and engineer selection) was incorporated. In general, the more elaborate decisions and agent interaction lead to higher demand for recycled materials, trending away from the currently observed demand.

Phase III, aiming at a better representation of the case study, included explicit material flows, updating of image and economic criteria according to system variables and further restriction on the decision option availability. *(i) Explicit material flows* did not change the main output measure much (cf. version 3.0 vs. 3.1). However, allowing for different project sizes and limiting the materials available according to expected flows of construction waste increased the credibility of the model in discussions with stakeholders. *(ii) Updating image, trend and price criteria* according to materials applied had similar small effects on the demand. *(iii) Restricting the availability of the decision options* brought the fairly high demand levels down to currently observed values. Enabled by the explicit materials modelled, in a first step only available recycled materials could be offered in a tender (cf. version 3.3) reducing the demand by about one third. In the final step (i.e. version 3.4) the link between sustainable construction and recycled concrete was limited. This means, that if sustainable construction was specified in project it only led to the consideration of recycling concrete as an option in 50% of the cases. Such a limitation was not only recommended by construction experts, as sustainable construction seems to be predominantly related to energy issues, but also revealed more realistic demand on the system level.

The role of empirically based decision parameters: In short, the most realistic demand representation was reached when option awareness and limitation was included in addition to the actual empirically based multi-criteria decision represented as discrete choices. The large empirical foundation for agents' decision and behaviour had not only an impact on the final representation of the model but already on the model development. Having the data ready might tempt an early implementation of the full complexity of agents' interaction and multi-criteria decisions. However, we strongly recommend an incremental inclusion and analysis of the model features. This unravels the key aspects of the decision model implemented (e.g. multi-criteria and discrete choice) as well as neglected aspects such as the option awareness. It further allows for tracking the effect of each additional feature on the result and therefore avoiding the pitfall of overly complex models with blurred explanatory power.

2.2 Model specification

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing agent-based models (Grimm et al. 2006; Grimm et al. 2010; Polhill 2010). The purpose of the model; entities, state variables and scales captured; and the process overview and design concepts are listed below. Detailed descriptions of the model's initial state, required input data, and submodel processes are provided in section 1.3 of the supporting information (SI).

2.2.1 Purpose of the model

This model aims at representing the decision-making and behaviour of interacting construction stakeholders when deciding what kind of construction material to apply. It was designed to analyse key factors affecting the demand for conventional materials (i.e. conventional concrete with natural gravel and sand aggregates) or recycled materials (i.e. recycled concrete where natural aggregates are substituted to a certain extent with recycled aggregates), and to develop scenarios leading to a maximal reuse. The main output variable considered is therefore the fraction of recycled concrete applied. The main driver of the model is construction investments broken down into projects to be executed by construction stakeholders.

2.2.2 Entities, state variables, and scales

Entities and state variables: The following entities are included in the model: agents representing construction stakeholders (i.e. awarding authorities, engineers, architects and contractors), projects, grid cells (i.e. virtual geographical location) and the global environment representing the construction market (i.e. construction investments and materials available).

Awarding authorities represent private persons, companies, or public authorities awarding prime building contracts, for different purposes (e.g. personal use, economic reasons, public building requirements). *Engineers* represent the actors responsible for the static design of the concrete structure in buildings; *architects* the stakeholders designing and supervising the construction, and c*ontractors* the companies providing the concrete work. All agents are located at a unique location and hold an identity number, construction related variables, such as construction capacity, building radius and experience, and multi-criteria decision variables for each distinct decision. In total, 5788 agents are implemented, representing the statistical distribution of construction stakeholders in the case study. *Projects* represent the individual construction projects on which these agents interact. Besides the basic project variables such as construction year, sum, investor type and material amount and type applied, the projects track the agents involved and the outcome of all agents' decisions. Per year about 450 projects are executed. *Grid cells* represent virtual construction sites of 30x30m. (A complete list of entities' state variables is provided in the SI Table 1). The *observer or global environment* (i.e. construction market) is the only entity on the system level, defining the annual construction investments and the potential recycling aggregates supply. In addition it holds the variables for demand and supply accounting and agent specific parameters for scenario measures (a complete list of global environment state variables and parameters is provided in the SI Table 2).

Model, spatial and temporal scales: The model was designed to represent individual construction projects with a model to reality relation of 1:100 (in terms of agents and projects). This means that 100 times less agents are represented in the model and each construction project is 100 times larger, respectively. The model has no explicit spatial relation; however, agents are distributed randomly across a virtual space for local interaction. The virtual space is an unwrapped square (to see edge effects) of 300 x 300 grid cells theoretically representing an area of 3x3km. Agents' building radii were derived from Knoeri et al. (2011b) and were adjusted to the model scale (e.g. mean building radius of 30 units (0.3km) for commercial and private awarding authorities and 50 units (0.5km) for public awarding authorities). One time step represents one year and simulations were run for 40 years (2010-2050) for material flow analysis and for 10 years (2010-2020) for the demand sensitivity analysis.

2.2.3 Process overview and scheduling

To set up the model all investment and material flow parameters as well as the initial number of agents are initialized. The main procedure, being executed every time step (i.e. year) by the observer, consists of the following five steps. First, the annual construction investments are calculated and accordingly this year's projects created. Second, the potential supply of recycled aggregates is calculated. Third, the projects are distributed to enough awarding authorities and randomly executed (i.e. if the number of projects exceeds the construction capacity of the awarding authorities new ones are created). Fourth, the global demand values and agent properties are updated according to the projects finished. Fifth and finally, the projects older than the limits of the agent's memory are erased from the model.

The most important sub model is the "execute project" procedure presented in Figure 1 which itself contains several subroutines (a complete specification of the subroutines is presented in SI Table 5). This project execution of the awarding authorities basically reflects the agent interaction chain derived from the agent-operationalization approach (Knoeri, et al. 2011a, 2011b). Once a project is assigned to an awarding authority, if sustainable construction is an option at all, this agent first makes his project specification, followed by selecting an engineer to get a design specification and an architect for a project recommendation. These selections are both based on neighbourhood, personal contacts and references. Engineer and architect interact through the project as the architect considers the engineer's design specification as a criterion, which is stored in the project. Having the recommendation from the experts, the awarding authority makes the project confirmation decision and selects the three closest contractors for tendering. Including tender price and expert recommendation the awarding authority awards the contract to the contractor with the highest utility. If the proposed recycled aggregates are out of stock the agents switch back to conventional materials. Finally the demanded materials are deducted from the market and assigned to the project. The availability of the recycling option for the construction experts (i.e. engineers, architects and contractors) depends on other agents' specifications or recommendation and own preferences. For example, engineers consider recycled concrete only as an option, either if the awarding authority specified sustainable construction and the engineer pursues by relating that to recycled concrete, or if he comes up with the recycling option by himself. In all other cases he recommends conventional concrete. The empirical data for the application specific decisions (e.g. from design specification to tender selection) were aggregated from decisions regarding structural indoor and outdoor concrete application since they have been found to correspond to a large extent (Knoeri, et al. 2011b). Lean concrete application decisions were neglected due to their relatively small contribution (< 4%) to the overall concrete flows (SI Figure 5).

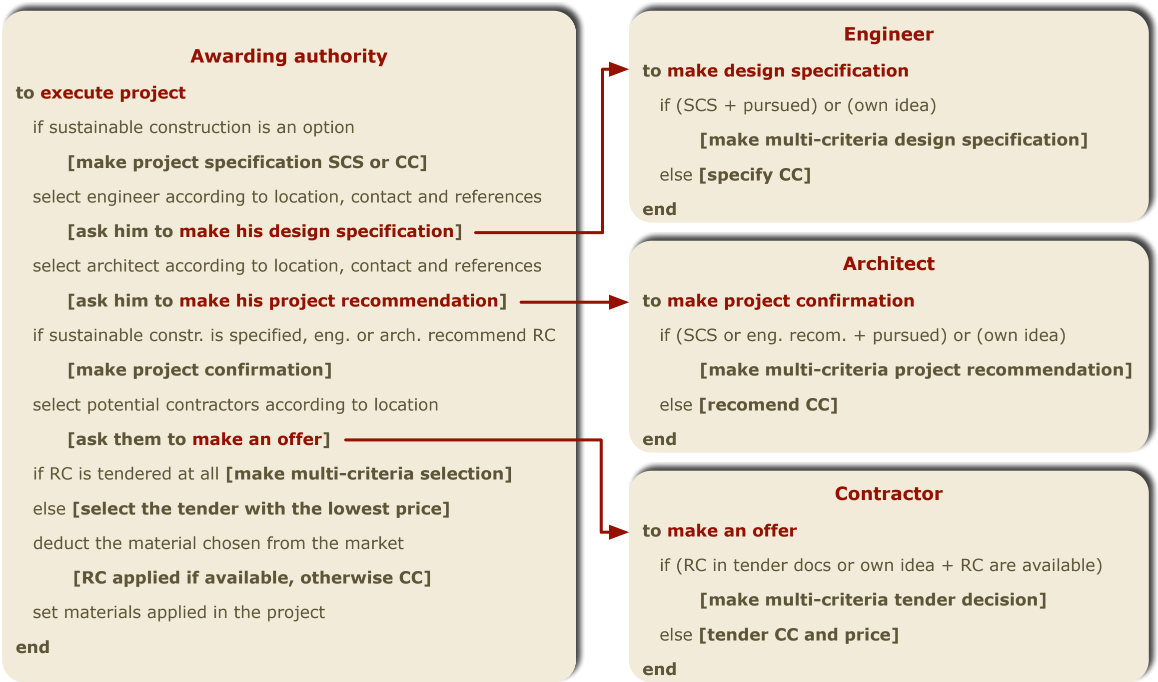

Figure 1: Pseudo-code of awarding authorities' project execution subroutine calling of engineers', architects' and contractors' subroutines (Sustainable construction specification (SCS), conventional concrete (CC), recycled concrete (RC)).

2.2.4 Implementation

The model is implemented in Netlogo 5.0 (Wilensky 1999) and source code is provided at the www.openabm.org model archive (http://www.openabm.org/model/3294/version/2/view).

2.2.5 Design Concepts

In the following we briefly present the main design concepts applied to the model (More detail is provided in SI section 1.2). Please see Railsback (2001) and Grimm et al. (2010) for further readings on design concepts.

Basic principles: Agent were operationalized with the agent-operationalization approach (Knoeri, et al. 2011a). Individual decision-making processes were modelled as multi-criteria decisions based on the analytical hierarchy process (Saaty 1980, 1990). *Emergence:* The model was designed to explore the processes that give rise to the demand for recycled concrete. Therefore, the main output variable is the fraction of recycled materials applied emerging from the agent interaction. *Adaptation:* Agents adapt by including criteria from other agents and the environment in their multi-criteria decisions, and select agents by considering previous interactions and references. *Objectives:* Agents use optimisation traits in their multi-criteria decisions. *Learning:* As agents adapt their economic, image and experience parameters to the respective system values and their personal experience, they learn, although in a simple way, from their and the system's past. *Sensing:* Agents are aware of their internal decision variables, are able to scan relevant variables of other agents, but have limited information of the construction market. *Interaction:* The agents interact directly through the construction project with other agents, and affect each other indirectly through material consumption, competition, and systemic variables. *Stochasticity:* Stochasticity was used to represent the empirical distributions, control the scheduling, and induce variability for less important assets. *Observation:* The main output data is the global fraction of recycled concrete applied and the demand for different types of aggregates on the system level.

3. Results and discussions

The results and discussion section is structured along the main question raised in the introduction: How can recycling of construction materials be enhanced? We first analyse the key factors affecting the demand for recycling materials, and then examine what scenarios lead to maximal reuse of construction & demolition waste streams. In each section we describe the procedures and experiments conducted, present the results derived, and discuss their implication.

3.1 Enhancing recycling of construction materials

3.1.1 Key factors affecting demand

To enhance the recycling of construction materials we first asked how sensitive the demand for recycled mineral construction materials is to changes in different parameters, or what key factors affect the demand for recycling material. We analysed the sensitivity of the results to changes in the option awareness and price differences between the material options. The option awareness parameters were investigated over their whole bandwidth (0-1) while price difference was varied from -50% to +50%. The fraction of recycling materials in relation to the total amount of applied materials was the main measure of interest. Since the demand for recycled concrete stabilized after 10 simulation years, we simulated the interval from 2010-2020 and ran 20 experiments per parameter setting.

3.1.2 Recycling fraction sensitivity to changing option awareness and price

Awarding authorities sustainable construction consideration in the project specification: In this initial decision the option awareness reflects if the actors considered sustainable construction as an option or not, and was varied for each awarding authority group separately. The overall recycled concrete fraction increased steadily with increasing option awareness of commercial and private awarding authorities, while increasing the option awareness of public awarding authorities showed minor effects (Figure 2).

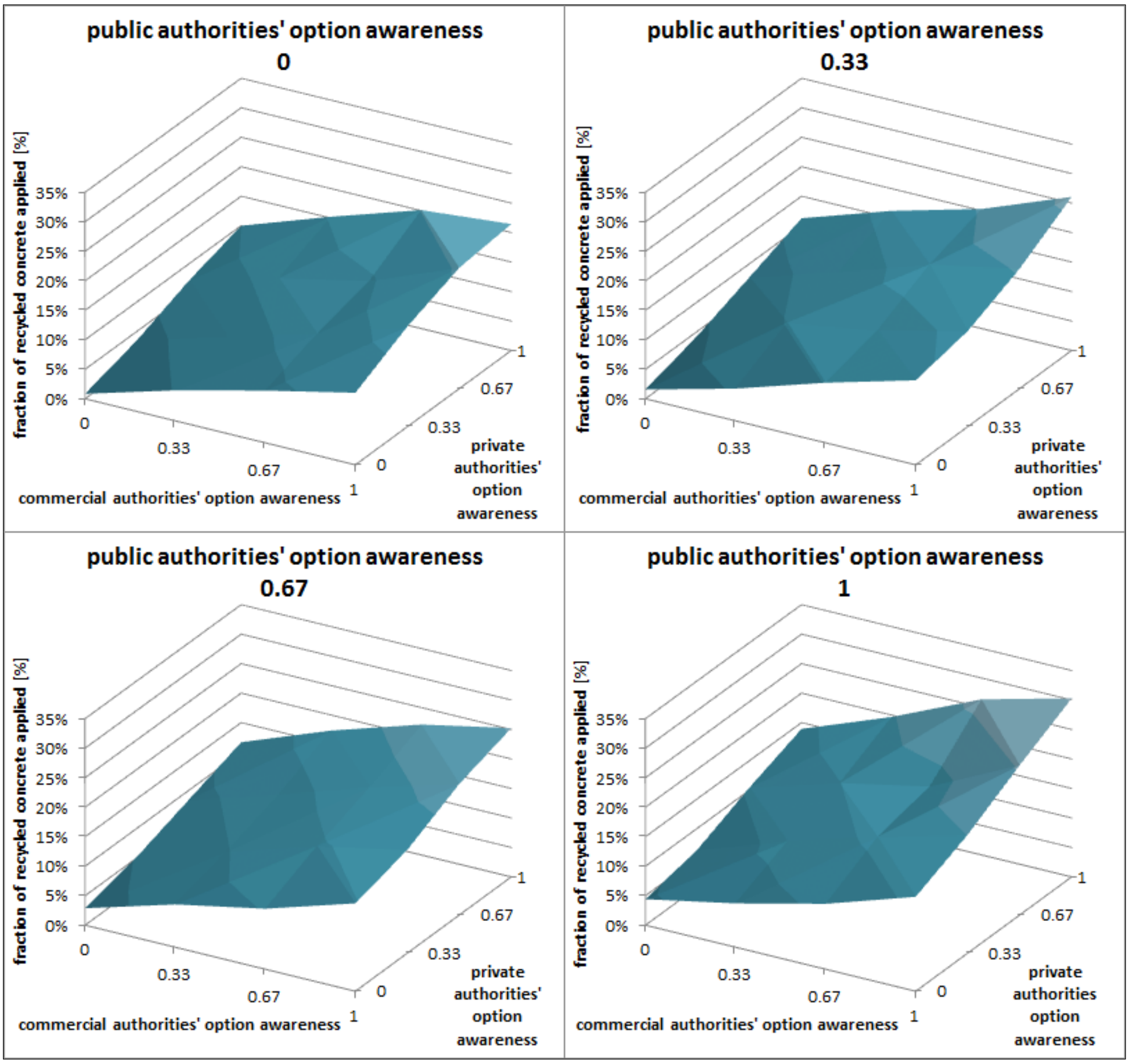

Figure 2: Sensitivity of the recycled concrete fraction to changes in awarding authorities awareness for sustainable construction as an decision option (awarding authorities' option awareness is raised in four steps from 0 to 1, public awarding authorities' option awareness is increasing from graph to graph, fraction represents mean values from 20 runs)

This basically reflects the share of the three groups on the overall construction investments (i.e. 50% commercial, 32% private, and 18% public investments) and therefore commercial and private authorities should be addressed. The observed reference values for the awareness of sustainable construction were 40% for public, 42% for commercial and 57% for private awarding authorities (Knoeri, et al. 2011b). This makes commercial awarding authorities definitely the agent group to address as they have the largest impact on the demand for recycled construction materials, and have among the lowest levels of awareness of all groups. Private awarding authorities have less potential for improvement as they already consider sustainable construction as an option in 57% of cases. In addition, their large number and the relatively small effect of each individual project make them the most difficult group to address. Public awarding authorities may have less direct impact on the system but might function as a role model when improving their option awareness.

Engineers' and architects' sensitivity to previous decisions and recycled concrete awareness: The consideration of recycled concrete as an option in engineers' and architects' decisions depends on two parameters: (i) specification sensitivity (i.e. their probability to relate a sustainable construction specification from the awarding authorities with recycled concrete), and (ii) recycled concrete option awareness, (i.e. their probability to come up with recycled concrete without sustainability or recycling being previously mentioned).

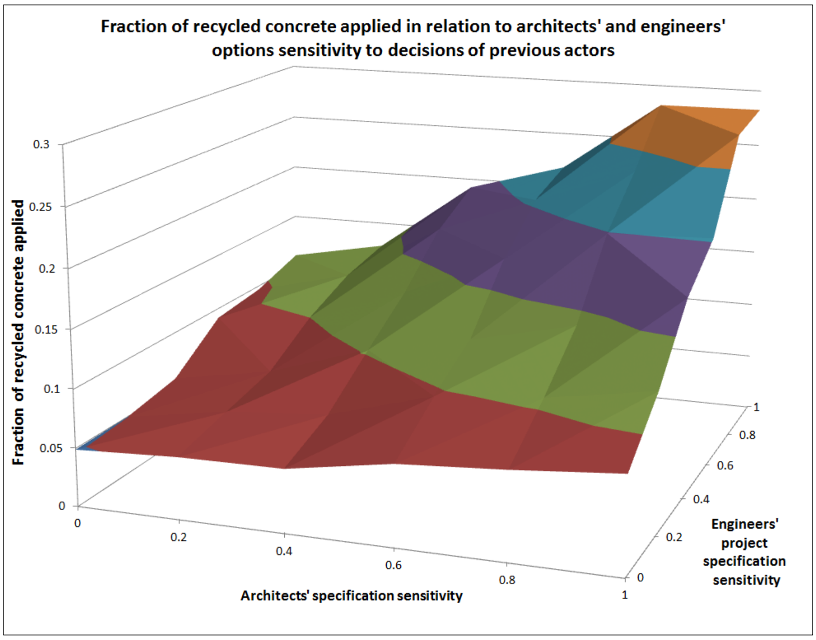

Figure 3: Recycled concrete fractions' sensitivity to changes in architects` and engineers` sensitivity to the project specification (0 if they consider options independent from awarding authorities` project specification, 1 if sustainable construction is specified they always consider recycled concrete as an option, displayed are mean values from 20 runs per parameter setting)

Figure 3 shows that the recycled concrete fraction is sensitive to changes in both architects' and engineers' reaction to the project specification (specification sensitivity). While in the first half of the parameter range the fraction sparsely increases, it takes off in the second half to reach a plateau after 0.8. This implies that an improvement of architects' and engineers' linkage of sustainable construction with recycled concrete (default value 0.5) will trigger its demand. This is one of the measures already taken by the Swiss sustainable construction standardization association, Minergie, by including recycled materials in their newest label Minergie-Eco (Minergie 2014). Compared to architects' and engineers' reaction to project specification, their own recycled concrete option awareness has relatively little effect on the final demand (SI Figure 11). However, information campaigns about the use of recycled concrete in these two groups as proposed by Spoerri at al. (2009), will affect both parameters.

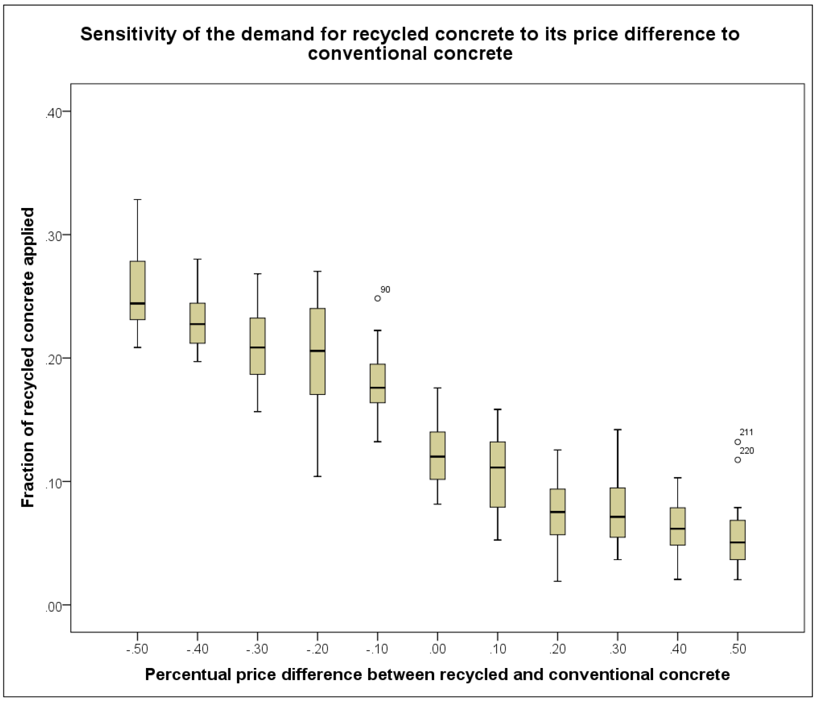

Figure 4: Boxplot of recycled concrete fractions' sensitivity to price differences in between recycled and conventional concrete [%]

Effects of price differences between recycled and conventional concrete: Price incentives is one of the most mentioned parameters to trigger the demand for recycled concrete among Swiss construction stakeholders (Knoeri, et al. 2011b). The results show that the recycled concrete demand is highly sensitive within a range of about 20% around equal prices. Above and below this range demand is relatively inelastic to further price incentives (Figure 4). The reason for the plateau when higher price differences are simulated is because price is just one criterion of several (i.e. 3-5) in construction stakeholders' multi-criteria decisions. For engineers, for example the average weight of expected costs is 22% while the other three criteria weight 78% together. This makes prices important enough to decide in decision situations in which the other criteria are balanced, if the other criteria clearly indicating one outcome, even large price differences are not able to turn the balance. Small price differences are therefore decisive for all agents with tight decisions or high weights for the price criteria, and higher price differences have little additional effect.

In conclusion, the fraction of recycling materials applied was most sensitive to stakeholders' awareness of the recycling option and price differences. In particular architects' and engineers' reaction to previous decisions in the agent interaction chain was a key factor. Further, the demand showed price elasticity in a particular range around current prices, while large differences had little additional effect.

3.2 Scenarios towards sustainable construction material management

3.2.1 Scenario development

For developing policy recommendations for possible intervention measures, several intervention scenarios were developed aiming at the identification of the parameter combination leading to a maximal reuse of construction & demolition waste streams. Three distinct (i.e. information, public initiative, and economic incentives) and two combined scenarios were developed based on the recycled concrete demand sensitivities found above and potential levers for policy interventions.

(i) Information: Awarding authorities' awareness of sustainable construction as a decision option is increased to 75% and architects and engineers consider recycled concrete as an option each time awarding authorities specify sustainable construction (i.e. 100% specification sensitivity). This scenario aims at simulating the effect of increased actors' awareness (i.e. probability of considering certain options) without changing their decision parameters.

(ii) Public initiative: Public awarding authorities' sustainable construction option awareness is increased to 100% (e.g. sustainable construction specification becomes standard for public construction works) and norms and standards are developed in favour of recycled concrete (i.e. from currently 0.45 to 0.75, where 0 favours conventional and 1 recycled concrete). This is to simulate the effect of isolated public efforts.

(iii) Economic incentives: For simulating and assessing the potential of taxes or subsidy measures, recycled concrete is given a 10% price advantage. (This is similar to the 10% price advantage for recycled concrete in the price sensitivity analysis above). This price advantage is perceived by the agents, as they increase the value (but not the weight) of their economic criteria by 10%.

(iv) Information and economic incentives: Combines the information scenario (i) with slight price advantages of 5%. Such price difference might be close to current practice in urban regions with recycling plants available (Eberhard 2014; HASTAG 2014).

(v) Information, economic incentives and norms: In addition to combining construction stakeholder information and price incentives (iv), the norms and standards, currently perceived slightly unfavourable for recycled concrete by the stakeholders (0.45), are improved towards favouring the recycling option (0.55).

The recycling fraction on its own allows conclusions about the recycled concretes' share on the overall concrete volume but not about how that relates to the construction & demolition waste amounts. In particular which of the two types of aggregates available, concrete rubble and mixed rubble, are demanded? Currently concrete rubble is the favourite recycling aggregate for structural concrete, (90% of the demand if both fractions are available). However, if concrete rubble runs out of stock, mixed rubble is demanded instead (see SI Table 5 execute project subroutine for details). In addition, the two currently applied recycled aggregate substitution fractions (i.e. amount of natural aggregates which are substituted with recycled aggregates currently between 25% and 40% (Knoeri, et al. 2013)) were analysed to avoid over estimation of construction & demolition waste reuse potential.

3.2.2 Recycling fraction and construction and demolition waste reuse in different scenarios

Figure 5 shows the resulting distribution of the recycling fraction per scenario. The information scenario increases the fraction of recycled concrete to almost 50% (mean 0.48, StD 0.04) of the concrete volume applied, while isolated public initiative (mean 0.17, StD 0.04), or 10% price differences (mean 0.19, StD 0.03) lead to just a slight improvement of recycled concrete demand compared to the reference value. However, combining even smaller economic incentives (5%) with information has by far a larger impact (mean 0.66, StD 0.03) on the overall recycled concrete fraction applied. Additional norm and standard enforcements however do not further increase the recycling fraction (mean 0.66, StD 0.02).

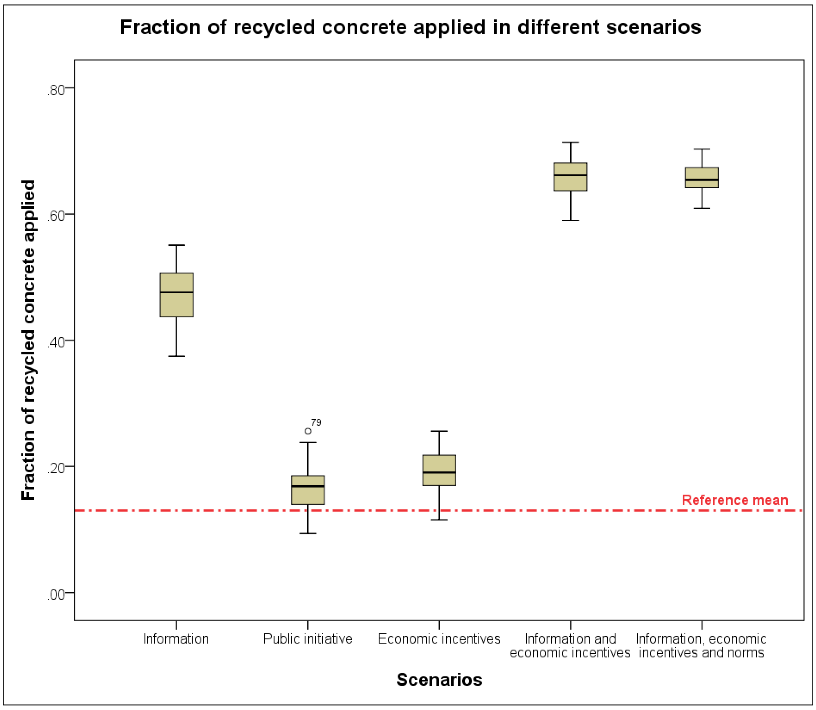

Figure 5: Resulting recycling concrete fraction applied in different scenarios (20 runs)

As shown in Figure 5 the scenarios including information campaigns lead to the highest reuse of construction & demolition waste (Figure 6). Even if only 25% of the aggregates in recycled concrete are recycled material in the information scenario, already most of the potential concrete rubble supply is demanded. Including small price incentives leads to a full reuse of the concrete rubble in the building sector and further increases the mixed rubble reuse. Shifting to 40% recycled aggregates in recycled concrete significantly increases the demand for mixed rubble (up to 50% of the potential supply) since concrete rubble runs out of stock faster.

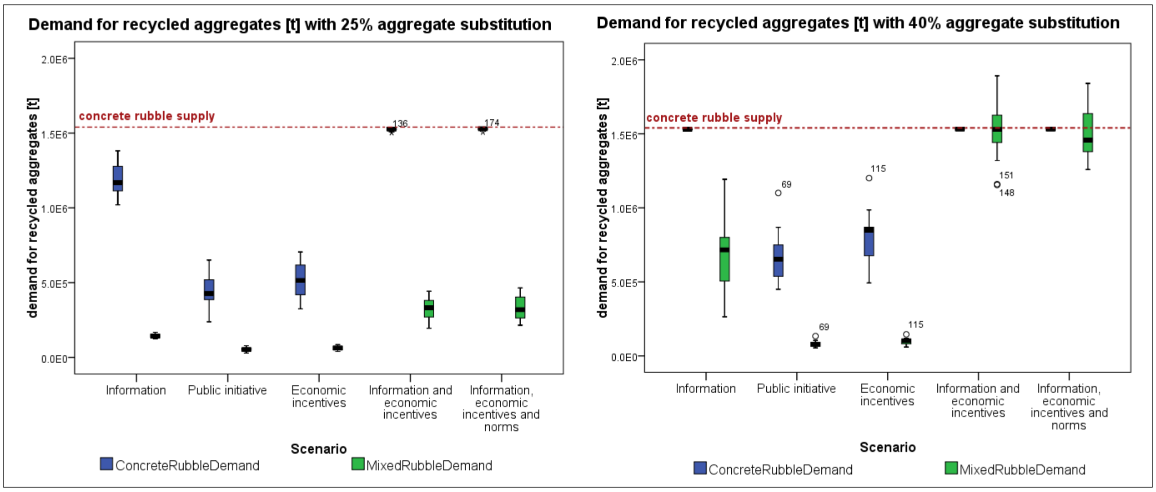

Figure 6: Annual demand for recycled aggregates (i.e. concrete rubble (blue boxes) and mixed rubble (green boxed)) **in different scenarios in comparison to the potential concrete rubble supply for two different aggregate substitution fractions,** (left 25%, right 40%) (20 simulation runs)**.**

3.2.3 Scenario implications

The most effective interventions for a transition towards a closed-loop mineral construction material management are extensive information campaigns combined with small price incentives. The campaigns should address in particular the construction experts (e.g. architects and engineers) and inform about the option of recycled materials. The stakeholder information considered in the model does not imply more recycled materials friendly decisions, since the decision parameters (i.e. criteria values and weights) remain unchanged as no significant differences between informed and uninformed stakeholders have been found empirically (Knoeri, et al. 2011b). It does, however, change the consideration of recycled materials as an option at all and therefore the stakeholders option awareness. Small price incentives (about 5%) as currently observed in urban regions in combination with information campaigns might be sufficient to enhance the use of recycled materials. However, the simulation results show that even though the demand for mixed rubble might be as high as the one for concrete rubble, it still stays far below its' potential supply, as mixed rubble has a 3 times higher share on the construction & demolition waste (SI Table 6). This implies that a recycled concrete demand fraction of almost 70% is still insufficient for a complete reuse of construction & demolition waste streams. Such complete reuse will require a shift towards recycled concrete as a standard (100% application) or higher aggregate substitution rates. This might lead to unintended consequences though, such as increasing environmental impacts due to larger transport distances and higher cement demand required to produce recycled concrete of the same quality as conventional concrete with increased aggregate substitution. Knoeri et al. (2013) showed that differences in transport distances larger than 15km or additional cement contents above 30kg per m^3 lead to higher environmental impacts than comparable conventional concrete. These thresholds might be exceeded by measures pushing the application toward recycled concrete only and in particular when high aggregate substitution rates are promoted.

4. Conclusion and further research

This paper explores the role of empirically based agent decision parameters for realistic system representation with the case study of Swiss construction actors` decisions towards recycling.

We showed that the most realistic representation of the demand for recycling concrete was reached when the option awareness was included in addition to the empirically based multi-criteria decisions, which we represented as discrete choices. The demand for recycled concrete was found to be most sensitive to changes in construction stakeholders' awareness of the recycling option and price differences between conventional and recycled material. The scenario analysis showed that a combination of extensive information campaigns and small price advantages for recycled materials would lead to a maximal reuse of construction and demolition waste. Further research should therefore concentrate on analysing how to raise construction stakeholders' awareness of recycled mineral construction material as a material option early on in the construction / design process.

From an ABM perspective there were two main lessons learned from the example: first, empirically based agents' decision-making and behaviour drastically decreases the degrees of freedom in the model and increase the confidence in the model performance when presenting the outcome to stakeholders, similar to the findings of collaborative modellers. Second, the fact that actors' option awareness were the most sensitive parameters but had little empirical foundation clearly advocates more model iterations and early simulation runs with dummy data. Analysing how to balance the effort on modelling and empirical data collection in relation to model result might be a promising strand of further research for context specific ABM developments. Besides this, the question of how to increase the option awareness relates to concepts such as knowledge diffusion and percolation (Cantono & Silverberg 2009; Delre et al. 2010). To further unravel this question and analyse how innovation diffusion depends on social influences, networks, attitudes and norms, ABM seems to be a promising way forward.

Acknowledgements

The authors thank all the experts for their support, time and knowledge; the three anonymous reviewers for their helpful comments; Chris Davis for commenting on the modelling process, Jonathan Busch for editing the text; and FEDRO (Swiss Federal Roads Office), FOEN (Federal Office for the Environment), AWEL (Amt für Abfall, Wasser, Energie und Luft; Environmental Agency) of the Canton of Zurich, AHB (Amt für Hochbauten; Office for structural engineering) of the City of Zurich and Eberhard Recycling AG for funding the study.

References

Andrews, C. J., Yi, D., Krogmann, U., Senick, J. A., & Wener, R. E. (2011). Designing Buildings for Real Occupants: An Agent-Based Approach. *IEEE Transactions on Systems Man and Cybernetics Part a-Systems and Humans, 41*(6), 1077-1091.

Axtell, R. L., Andrews, C. J., & Small, M. J. (2001). Agent-Based Modeling and Industrial Ecology. *Journal of Industrial Ecology, 5*(4), 10-13.

Bergman, N., Haxeltine, A., Whitmarsh, L., Kohler, J., Schilperoord, M., & Rotmans, J. (2008). Modelling socio-technical transition patterns and pathways. *Journal of Artificial Societies and Social Simulation, 11*(3), 1460-7425.

Bergsdal, H., Brattebo, H., Bohne, R. A., & Mueller, D. B. (2007). Dynamic material flow analysis for Norway's dwelling stock. *Building Research and Information, 35*(5), 557-570.

Bollinger, L. A., Davis, C., Nikolić, I., & Dijkema, G. P. J. (2011). Modeling Metal Flow Systems. *Journal of Industrial Ecology*.

Cantono, S., & Silverberg, G. (2009). A percolation model of eco-innovation diffusion: The relationship between diffusion, learning economies and subsidies. *Technological Forecasting and Social Change, 76*(4), 487-496.

Chappin, E. J. L., & Dijkema, G. P. J. (2010). Agent-based modelling of energy infrastructure transitions. *International Journal of Critical Infrastructures, 6*(2), 106-130.

Davis, C., Nikolic, I., & Dijkema, G. P. J. (2010). Industrial Ecology 2.0. *Journal of Industrial Ecology, 14*(5), 707-726.

Delre, S. A., Jager, W., Bijmolt, T. H. A., & Janssen, M. A. (2010). Will It Spread or Not? The Effects of Social Influences and Network Topology on Innovation Diffusion. *Journal of Product Innovation Management, 27*(2), 267-282.

Eberhard. (2014). Baustoffe 2014 [Construction materials 2014]. Retrieved 09.06.2014, from http://www.eberhard.ch/dnl/104_1275_RC_Primaerbaustoffe_Peisliste_2014-2.pdf

FOEN. (2001). *Bauabfälle Schweiz - Mengen, Perspektiven und Entsorgungswege. Band 1: Kennwerte [Construction and demolition waste in Switzerland - amounts, perspectives and disposal routes. Volume 1: Statistical values].* Bern: Federal Office for the Environment (FOEN).

FOEN. (2008). *Bauabfaelle Hochbau in der Schweiz; Ergebnisse der Studie 2008 [Swiss buildings` construction waste; Results from a 2008 study)*. Bern, Switzerland: Federal Office for the Environment.

Garcia, R. (2005). Uses of agent-based modeling in innovation/new product development research. *Journal of Product Innovation Management, 22*(5), 380-398.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., et al. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling, 198*(1-2), 115-126.

Grimm, V., Berger, U., Deangelis, D., Polhill, G. J., Giske, J., & Railsback, S. F. (2010). The ODD protocol: a review and first update. *Ecological Modelling, 221*(23), 2760-2768.

Grimm, V., & Railsback, S. F. (2005). *Individual-based Modeling and Ecology*: Princeton University Press.

Hashimoto, S., Tanikawa, H., & Moriguchi, Y. (2007). Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. *Waste Management, 27*, 1725-1738.

HASTAG. (2014). Products and Prizes 2014. Retrieved 09.06.2014, from http://www.hastag.ch/data/docs/download/8397/de/HASTAG-PL2014-light.pdf

Haxeltine, A., Withmarsh, L., Bergman, N., Rotmans, J., Schilperoord, M., & Kohler, J. (2008). A Conceptual Framework for transition modelling. *International Journal for Innovation and Sustainable Development, 3*(1/2).

Hoffmann, C., & Leemann, A. (2006). *Recycled concrete and mixed rubble as aggregates: Influence of variations in composition on the concrete properties.* Paper presented at the Advances in Cement and Concrete X: Sustainability Davos, Switzerland.

Janssen, M. A., & Ostrom, E. (2005). Governing social-ecological systems. In L. Tesfatsion & K. L. Judd (Eds.), *Handbook of computational economics II: agent-based computational economics*. Amsterdam, The Netherlands: Elsevier.
Janssen, M. A., & Ostrom, E. (2006). Empirically based, agent-based models. *Ecology and Society, 11*(2).
Knoeri, C., Binder, C. R., & Althaus, H. J. (2011a). An agent operationalization approach for context specific agent-based modeling. *JASSS The Journal of Artificial Societies and Social Simulation, 14*(2).
Knoeri, C., Binder, C. R., & Althaus, H. J. (2011b). Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials. *Resources, Conservation and Recycling, 55*(11), 1039-1050.
Knoeri, C., Sanyé-Mengual, E., & Althaus, H. J. (2013). Comparative LCA of recycled and conventional concrete for structural applications. *International Journal of Life Cycle Assessment, 18*(5), 909-918.
Ling, Y. Y. (2002). A conceptual model for selection of architects by project managers in Singapore. *International Journal of Project Management, 21*(2003), 135-144.
Louie, M. A., & Carley, K. M. (2008). Balancing the criticisms: Validating multi-agent models of social systems. *Simulation Modelling Practice and Theory, 16*(2), 242-256.
Marinkovic, S., Radonjanin, V., Malesev, M., & Ignjatovic, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management, 30*(11), 2255-2264.
Minergie. (2014). Minergie-Eco. Retrieved 09.06.2014, from http://www.minergie.ch/minergie-ecop-eco.html
Moser, K., Bertschinger, H., Hugener, M., Richner, P., & Richter, K. (2004). *Baustoffmanagement 21 an der EMPA, Stand des Wissens und Forschungsbedarf [Management of construction materials at EMPA: state of knowledge and need for further research]* (Schlussbericht): Material Science and Technology (EMPA).
Parker, C., Manson, S. M., Janssen, M. A., Hoffmann, M. J., & Deadman, P. (2003). Multi-agent systems for the simulation of land-use and land-cover change; a review. *Annals of the Association of American Geographers, 93*(2), 314-337.
Polhill, J. G. (2010). ODD Updated. *Journal of Artificial Societies and Social Simulation, 13*(4), 9.
Polhill, J. G., Parker, D., Brown, D., & Grimm, V. (2008). Using the ODD Protocol for Describing Three Agent-Based Social Simulation Models of Land-Use Change. *Jasss-the Journal of Artificial Societies and Social Simulation, 11*(2).
Rahmandad, H., & Sterman, J. (2008). Heterogeneity and network structure in the dynamics of diffusion: Comparing agent-based and differential equation models. *Management Science, 54*(5), 998-1014.
Railsback, S. F. (2001). Concepts from complex adaptive systems as a framework for individual-based modelling. [Article]. *Ecological Modelling, 139*(1), 47-62.
Ramanath, A. M., & Gilbert, N. (2004). The design of participatory agent-based social simulations. *Jasss-the Journal of Artificial Societies and Social Simulation, 7*(4).
Saaty, T. L. (1980). *The analytical hierarchy process: planning, priority setting, resource allocation*. New York: McGraw-Hill.
Saaty, T. L. (1990). How to Make a Decision - the Analytic Hierarchy Process. *European Journal of Operational Research, 48*(1), 9-26.
Sargent, R. G. (2008, Dec 09-12). *Verification and validation of simulation models.* Paper presented at the 2008 Winter Simulation Conference, Washington, DC.
Schachermayer, E., Lahner, T., & Brunner, P. H. (2000). Assessment of two different separation techniques for building wastes. *Waste Management & Research, 18*(1), 16-24.
Schwarz, N., & Ernst, A. (2009). Agent-based modeling of the diffusion of environmental innovations - An empirical approach. *Technological Forecasting and Social Change, 76*(4), 497-511.
Recyclingbeton [Recycling Concrete], SIA 2030 C.F.R. (2010).

Sopha, B. M., Klockner, C. A., & Hertwich, E. G. (2011). Exploring policy options for a transition to sustainable heating system diffusion using an agent-based simulation. *Energy Policy, 39*(5), 2722-2729.

Spoerri, A., Lang, D. J., Binder, C. R., & Scholz, R. W. (2009). Expert-based scenarios for strategic waste and resource management planning - C&D waste recycling in the Canton of Zurich, Switzerland. *Resources, Conservation and Recycling, 53*(10), 592-600.

Svenson, O. (1990). *Some propositions for the classification of decision situations*. Amsterdam: Elsevier Science Publ B V.

Tam, V. W., & Tam, C. M. (2006). A review on the viable technology for construction waste recycling. *Resources Conservation and Recycling, 47*(3), 209-221.

Weil, M., Jeske, U., & Schebek, L. (2006). Closed-loop recycling of construction and demolition waste in Germany in view of stricter environmental threshold values. *Waste Management & Research, 24*(3), 197-206.

Wilensky, U. (1999). NetLogo. Northwestern University, Evanston, IL: Center for Connected Learning and Computer-Based Modeling. http://ccl.northwestern.edu/netlogo.

Publication VI

Comparative LCA of recycled and conventional concrete for structural applications

Overview

This paper analyses the environmental impacts of recycled concrete (RC) and how they depend on concrete mixture, cement type and amount, aggregates composition and transport distances. Therefore, the life cycle impacts of 12 RC mixtures with two different cement types are compared with corresponding conventional concretes (CC) mixtures for three structural applications. The recycling mixtures were selected according to laws, standards and construction practice in Switzerland. We compared the environmental impacts for ready-for-use concrete on the construction site, assuming equal lifetimes for recycling and conventional concrete in a full LCA.

Main findings

- *Environmental benefits for RC:* The results show clear (~30%) environmental benefits for all RC options at endpoint level (ecoindicator 99 and ecological scarcity). Regarding global warming potential (GWP), the results are more balanced and primarily depend on the amount of cement added for RC.

- *Avoided burdens:* The difference mainly origins in the avoided burdens of pig-iron production and C&D waste disposal, from the recycled aggregates' production.

- *Additional cement and transport distances:* RC exhibits a GWP comparable to CC if the amount of additional cement per m3 of concrete exceeds 22 to 40 kg. Large additional transport distances (>15 to >50 tkm depending on indicator) for the RC options do result in higher environmental impacts as well.

Relevance for the doctoral thesis

With respect to the thesis this study contributed with analysing and comparing the environmental impacts of the different material options in structural engineering. It therefore provided the basis for policy and industry recommendations for a sustainable construction material management. Furthermore, it allowed synthesizing the material flow results from the agent based model with environmental impacts to make systemic assessments.

Comparative LCA of recycled and conventional concrete for structural applications

Knoeri Christof [a,c], Sanyé-Mengual Esther [b], Althaus Hans-Joerg [a]

[a] *Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Technology and Society, Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland*

[b] *Sostenipra (ICTA-IRTA-Inèdit) – Institute of Environmental Science and Technology. Universitat Autonoma de Barcelona (UAB). Campus de la UAB, 08193. Cerdanyola del Vallès, Spain.*

[c] *Sustainability Research Institute, School of Earth & Environment, University of Leeds*

International Journal of Life Cycle Assessment

Received: 11th January 2012 Accepted: 18th December 2012 Published: January 2013

Abstract

Purpose: Construction and demolition (C&D) waste recycling has been considered to be a valuable option not only for minimizing C&D waste streams to landfills but also for mitigating primary mineral resource depletion. However, the potentially higher cement demand due to the larger surface of the coarse recycled aggregates challenges the environmental benefits of recycling concrete. Furthermore, it is unclear how the environmental impacts depend on concrete mixture, cement type, aggregates composition and transport distances.

Method: We therefore analysed the life cycle impacts of 12 recycled concrete (RC) mixtures with two different cement types and compared it with corresponding conventional concretes (CC) for three structural applications. The RC mixtures were selected according to laws, standards and construction practice in Switzerland. We compared the environmental impacts of ready-for-use concrete on the construction site, assuming equal lifetimes for recycled and conventional concrete in a full LCA. System expansion and substitution are considered to achieve the same functionality for all systems.

Results: The results show clear (~30%) environmental benefits for all RC options at endpoint level (ecoindicator 99 and ecological scarcity). The difference is mainly due to the avoided burdens associated to reinforcing steel recycling and avoided disposal of C&D waste. Regarding global warming potential (GWP), the results are more balanced and primarily depend on the additional amount of cement needed for RC. Above 22 to 40 kg additional cement per m^3 of concrete, RC exhibits a GWP comparable to CC. Additional transport distances above 15 km for the RC options do result in environmental impacts higher than those for CC.

Conclusions: In summary, the current market mixtures of recycled concrete in Switzerland show significant environmental benefits compared to conventional concrete and cause similar GWP, if additional cement and transport for RC are limited.

Keywords: Construction & demolition waste, recycled concrete, life-cycle assessment, cement, transport

1 Introduction

1.1 Background

Concrete is the most heavily consumed material in the construction sector and the second most heavily consumed substance on Earth after water (ISO 2005; Weil et al. 2006). The estimated worldwide concrete consumption was between 21 and 31 billion tonnes in 2006 (WBCDS 2009). In addition, construction and demolition (C&D) waste has become the largest (Schachermayer et al. 2000; FOEN 2010) and increasing (Muller 2006; Bergsdal et al. 2007; Hashimoto et al. 2007; Hao et al. 2007) waste fraction in industrialized countries. Thus, C&D waste reuse as concrete aggregates has been considered as a valuable option to substitute the primary aggregates in concrete production (Blum and Stutzriemer 2007; Weil et al. 2006; Rao et al. 2007) as well as reducing the C&D waste deposition (Lawson et al. 2001; Hiete et al. 2011; Woodward and Duffy 2011), where space for landfills is increasingly scarce (Duran et al. 2006; WBCDS 2009). In the European Union, where the average C&D waste recycling rate is 33% (Eurostat 2009), the most recent waste legislation established a material recovery rate target of 70% for 2020 for this group of wastes (including reuse, recycling or other material recovery) (EC 2008). In the Netherlands, concrete landfilling is banned and the recycling rate is 100% (apart from some residual process waste) (WBCDS 2009).

In Switzerland about 80% of the C&D waste is recycled (FSO 2010). This comparably high recycling rate is mainly due to high on-site recycling rates in civil engineering[4], where about 94% of the C&D waste is reused (FOEN 2001, 2005). C&D waste from structural engineering[5] is usually down-cycled (i.e. used in low-grade applications such as lean concrete) or landfilled (Spoerri et al. 2009; FOEN 2001; Knoeri et al. 2011). The technical potential for use of recycled concrete (RC) in structural concrete applications has been demonstrated in various research projects (Hoffmann and Jacobs 2007; Li 2008; Poon et al. 2009; Rao et al. 2007). In addition, these applications are already defined in legislation and standards (KBOB 2007; SIA 2010; FOEN 2006) and reference projects have demonstrated their practicability (Hofmann and Patt 2006).

However, environmental benefits of high grade RC applications have been in doubt (Holcim 2010). Since cement is the main contributor to many environmental impacts (e.g. GWP[6]) of concrete, additional cement use for RC due to the larger grain surface area of recycled aggregates (Fonseca et al. 2011; Cabral et al. 2010; Limbachiya et al. 2007; Hoffmann and Jacobs 2007) might outweigh potential benefits of natural aggregate substitution (Weil et al. 2006). In previous studies, the RC aggregate percentages ranged from 25% (Holcim 2010) to 100% (Fonseca et al. 2011) and, consequently, additional cement content ranged from zero (Fonseca et al. 2011) to 30kg (Weil et al. 2006). Furthermore, the substitution of C&D waste disposal and steel production through recycling of (reinforced) concrete is neglected in previous life cycle

[4] Civil engineering is defined as the design and construction of roads, bridges, tunnels water and electricity supply and sewerage (i.e. mainly publicly contracted works).

[5] Structural engineering is defined as the design and construction of buildings.

[6] GWP: Global warming potential [kg CO_2 eq.]

assessment (LCA) studies (Weil et al. 2006; Marinkovic et al. 2010; Holcim 2010). In addition, transport distances and types (Marinkovic et al. 2010), and C&D waste treatment (Mercante et al. 2011) have been found to significantly affect the balance of RC. This implies that environmental benefits of different RC mixtures in comparison with conventional concrete (CC) are still in doubt. Furthermore is the sensitivity of such comparison to additional cement for RC, C&D waste composition, and different transport distances yet unclear.

2 Materials and Methods

2.1 Goal and scope

This project aims to establish a comparative LCA of conventional concrete (CC) and recycled concrete (RC) and to analyse the effect of cement content and transport distances. Allocation is avoided by system expansion and substitution according to ISO 14044 (ISO 2006). The results will provide policy recommendations for construction waste management and support construction stakeholders' decisions (i.e. awarding authorities, engineers, architects and contractors (Knoeri et al. 2011)). The system includes all processes from aggregates' extraction (CC) and building dismantling (RC) to ready-for-use concrete on the construction site. The construction process and the use phase of conventional and recycled concrete structures are assumed to be comparable and are therefore omitted from the analysis. Consequently, the functional unit is 1 m^3 of concrete of a specific strength class at the construction site.

The production of recycled aggregates for RC requires additional treatment (i.e. crushing and sorting) of the C&D waste in stationary or mobile recycling plants. During this process additional iron scrap is recovered from C&D waste compared to building dismantling (Eberhard 2011; Doka, 2009; Hächler and Frei 2005). Therefore, environmental benefits from co-products of the recycling operation (i.e. the disposal service for C&D waste and the steel scrap recovered in the process) were considered as avoided impacts, to ensure the same functionality of the RC and CC product systems (Fig.1). The life cycle inventory (LCI) data for concrete production and C&D waste recycling were compiled specifically for this study, while the LCI data for materials and processes in the background system are taken from the ecoinvent database version 2.2. The impact assessment was performed using two endpoint methods (Ecoindicator 99 and Ecological Scarcity 2006) and Global Warming (GWP) and Abiotic Depletion (ADP) potentials as midpoint indicators.

2.2 System description

Fig.1 shows the conventional concrete and the recycled concrete production systems considered. Both systems include raw materials production (i.e. aggregate extraction, cement and additive production and water supply) and fly ash as inputs including their transport stages (i.e. T1-T4), and produce concrete as an output transported to the construction site (T7). The recycled concrete system further includes dismantling, C&D waste treatment (i.e. operation of the recycling plant), and the related transports (i.e. T5 and T6). Moreover, the recycling concrete system considers the avoided impacts related to the reuse of C&D waste. These are the avoided disposal of C&D waste and its transport (T8), as well as the avoided impacts related to the recovery of iron scrap obtained from the recycling plant (Fig.1).

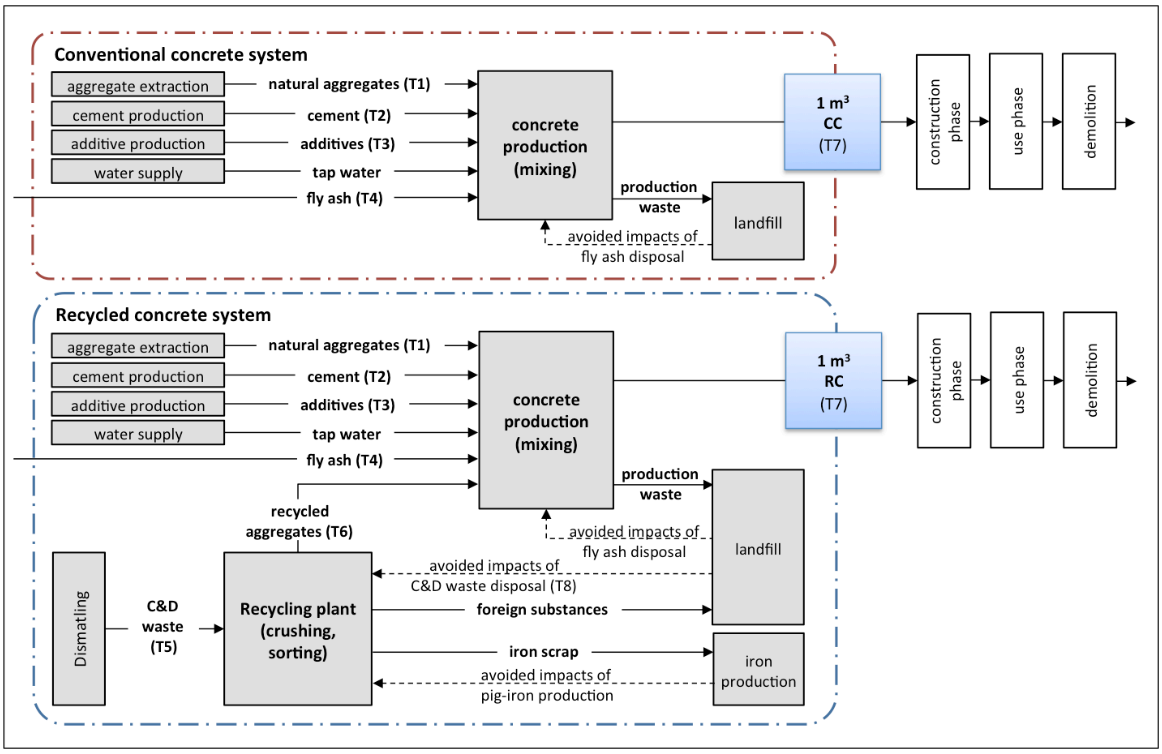

Fig. 8 System boundaries, processes and materials for the conventional concrete and the recycling concrete systems (Light blue box indicates reference products, grey boxes processes, solid arrows product flows and dotted arrow avoided impacts considered. Transport is specified for each product according to SI Table 5)

Table 1 shows the applications, concrete types, aggregates and cement content considered in the scenarios. Three different concrete qualities were investigated since different applications require different technical standards (SIA 2002) and exhibit different acceptance of RC materials (Knoeri et al. 2011): lean concrete (LC) (150/200kg cement / m^3), indoor concrete (IC) (C25/30[7], NPK[8] A/B) and outdoor concrete (OC)(C30/35, NPK C) (Supporting information (SI) Table 1). The standardized recycling options, recycled concrete from concrete aggregates (RC-C) using concrete rubble and recycled concrete from mixed aggregates (RC-M) using mixed rubble (KBOB 2007; SIA 2010; FOEN 2006; SIA 2002), were specified for each concrete quality analysed. Two scenarios were modelled for each recycled option: a reference scenario, considering the percentage (40%) of recycled aggregates to obtain additional points for the Minergie-Eco label (Minergie 2007), and a minimum scenario (25% recycled aggregates), according to standards (SIA 2010). Finally, different cement types and content levels are considered. The scenario mixtures are denominated according to their application (e.g. OC), concrete type (e.g. RC-C), percentage of recycled aggregates substituted (e.g. ref), cement amount (e.g. CEM 310) and cement type (e.g. Portland calcareous).

[7] Concrete strength class: Comprehensive strength of a cylinder/cube after 28 days curing [N/mm^2] (SIA 2002)

[8] NPK: Swiss construction sector standardization (Normpositionenkatalog) (CRB 2011)

Table 1 Applications, concrete types, aggregates and cement amount considered, and corresponding denominations. ([a] Since two types of cement (i.e. Portland cement CEM I 42.5 and Portland calcareous CEM II) are investigated, the denominations are extended with the cement considered (e.g. IC-CC Portland 42.5 or IC-CC Portland calcareous))

Appli-cation	Concrete type	Aggregate scenarios: Recycled aggregates source	Aggregate scenarios: (% of recycled aggregates)	Aggregates [kg / m^3 concrete]	Natural aggre-gates [M.-%]	Con-crete rubble [M.-%]	Mixed rubble [M.-%]	Cement (CEM) [kg / m^3 concrete]	Denomination [a]
Outdoor concrete **(OC)**	Conventional concrete **(CC)**			1890	100			**300**	OC CC
	Recycled concrete **(RC)**	Concrete rubble **(C)**	**min** (25%)	1784	72	28		**300**	OC RC-Cmin CEM300
								310	OC RC-Cmin CEM310
								320	OC RC-Cmin CEM320
			ref (40%)	1624	55	45		**300**	OC RC-Cref CEM300
								310	OC RC-Cref CEM310
								320	OC RC-Cref CEM320
		Mixed rubble **(M)**	**min** (25%)	1526	70		30	**300**	OC RC-Mmin CEM300
								320	OC RC-Mmin CEM320
								340	OC RC-Mmin CEM340
			ref (40%)	1374	50		50	**300**	OC RC-Mref CEM300
								330	OC RC-Mref CEM330
								360	OC RC-Mref CEM360
Indoor concrete **(IC)**	Conventional concrete **(CC)**			1890	100			**280**	IC CC
	Recycled concrete **(RC)**	Concrete rubble **(C)**	**min** (25%)	1784	72	28		**280**	IC RC-Cmin CEM280
								290	IC RC-Cmin CEM290
								300	IC RC-Cmin CEM300
			ref (40%)	1624	55	45		**280**	IC RC-Cref CEM280
								290	IC RC-Cref CEM290
								300	IC RC-Cref CEM300
		Mixed rubble **(M)**	**min** (25%)	1526	70		30	**280**	IC RC-Mmin CEM280
								305	IC RC-Mmin CEM305
								330	IC RC-Mmin CEM330
			ref (40%)	1374	50		50	**280**	IC RC-Mref CEM280
								310	IC RC-Mref CEM310
								340	IC RC-Mref CEM340
Lean concrete **(LC)**	Conventional concrete **(CC)**			1890	100			**150**	LC CC CEM150
								200	LC CC CEM200
	Recycled concrete **(RC)**	Mixed rubble **(M)**	(100%)	1221			100	**150**	LC RC CEM150
								200	LC RC CEM200

2.3 Life Cycle Inventory (LCI)

The model for the concrete components (i.e. cement, aggregates, additives, filler and water), for the C&D waste composition and for transport distances is described below. Background data is taken from the ecoinvent database version 2.2. Table 1 shows an overview of the mixtures analysed, while complete mixture descriptions and LCIs are provided in SI Table 5-7.

Cement: A minimum cement content level is considered for each application in CC mixtures according to the quality requirements (SIA 2002). Three cement content scenarios were defined for the structural RC options in collaboration with RC producers (Strauss 2011; Eberhard 2011) to assess the sensitivity of environmental performance: no additional cement, a reference scenario, and a maximal level of additional cement for RC. For lean concrete no additional cement is required. Finally, two types of cement (i.e. Portland cement CEM I 42.5 and Portland calcareous CEM II) were investigated for structural concrete, covering 98% of the cement used in Switzerland (Cemsuisse 2011), while for lean concrete only Portland calcareous is used.

Aggregates: Round gravel is considered as natural aggregate, since crushed gravel represents only 15% of the gravel used in Switzerland (Künniger et al. 2001). For 1 m^3 of CC 1890 kg of round gravel were considered (Künniger et al. 2001). Since recycled aggregates have a lower density, the total aggregates weight was reduced depending on the percentage of recycled aggregates used. Based on Holcim (2010), it is assumed that per 5% recycled aggregates, a 1% lower aggregate mass is needed in the mixture. Recycled aggregates were slightly (i.e. 28% or 50%) overdosed to reach the required (SIA 2010) minimum amount of recycled grains (e.g. 25% or 40%) in the aggregates mixture since 10-20% of natural grains are detected in the recycled aggregates' petrography (counting grains > 8mm) (SI Table 2-3).

Other components: Filler and additive inputs increase with the cement content and the application (i.e. higher amount is needed in higher quality applications). RC mixtures require 0.2% more additives than comparable CC mixtures. Fly ash is considered as filler and the substitution of its disposal is considered by avoiding the corresponding amount of fly ash disposal according to ecoinvent v2.2 (Doka, 2009). The amount of fly ash used does not differ from CC to RC. Finally, a higher additional water demand is assumed for RC as recycled aggregates have a larger surface area and are usually drier than natural aggregates (Eberhard 2011; Strauss 2011) (SI Table 5-7).

C&D waste composition: A mixed rubble composition of 70% waste concrete and 30% waste brick, and a concrete rubble composition of 95% waste concrete and less than 5% waste brick have been assumed according to practitioners (Eberhard 2011), the shares specified by law (FOEN 2006), and aggregates petrographic profile (Rubli 2011). A distribution of 70% reinforced concrete and 30% non-reinforced concrete in the concrete waste fraction was used based on (FOEN 2001). Assuming 3% (w/w) of steel in reinforced concrete (Doka, 2009), iron-scrap contents of 2% for concrete rubble and 1.5% for mixed rubble were obtained. This is in the same range as the empirical observed 1.2% (w/w) for a mixture of concrete and mixed rubble in a multipurpose recycling plant (Eberhard 2011; Hächler and Frei 2005). Foreign substances (i.e.

wood and plastics) for disposal account for less than 1% in the waste fractions, based on a recycling plant inventory (Hächler and Frei 2005). C&D waste disposal inventory data was obtained from the ecoinvent database (Doka, 2009).

Transport distances: Reference distances according to average data of Swiss concrete firms (Gschösser 2011) for the transport of natural aggregates, cement, additives (plasticizer) and filler (fly ash) were considered. They correspond well to the transport distances modelled so far in the ecoinvent database for concrete at plant (Kellenberger et al. 2007). These distances were held constant for natural aggregates, cement, additives and filler, while transport sensitivity analyses (reference, best case and worst case) were performed for the C&D waste, recycled aggregates and produced concrete (SI Table 4).

3 Results and Discussion

In the following, we present and discuss the overall environmental impact assessment results for all three applications (i.e. lean, indoor and outdoor structural concrete) and the sensitivities to a variation of cement types and contents, C&D waste compositions and transport distances for exemplified applications and mixtures.

3.1 Overall environmental impact assessment

3.1.1 Structural concrete

Fig. 2 shows that RC mixtures for structural concrete applications (OC and IC) have significant environmental benefits compared to CC with the same cement type (mean 31%, StD 9%) at endpoint level. The reduction depends on the concrete mixture and ranges from 15% (IC RC-Mmin, CEM330, Portland 42.5) to 50% (OC RC-Cref, CEM300, Portland calcareous). Strongly reduced “respiratory inorganics” effects and a slight reduction of fossil fuel consumption are the main contributions to the ecoindicator 99 reduction, while the ecological scarcity 2006 reduction is caused by natural resources preservation in addition to reduced emissions to air. Abiotic depletion potential (ADP) shows a similar picture with a clear ADP reduction for all RC options (mean 34%, StD 11%). But RC and CC have similar GWP due to higher cement content when recycled aggregates are used (mean reduction for RC 5%, StD 7%) (SI Fig. 1). All four assessment methods (ecoindicator 99, ecological scarcity 2006, ADP and GWP) show a clear difference between cement types used and amount of aggregates substituted. Concrete mixtures with Portland cement calcareous have consistently less (i.e. about 10%) environmental impacts than mixtures with cement 42.5. The more natural aggregates were substituted (e.g. 50% instead of 30%) the better the environmental assessment results, while the aggregate type (i.e. concrete rubble or mixed rubble) has less impact on the results (Fig. 1 and SI Table 8-9).

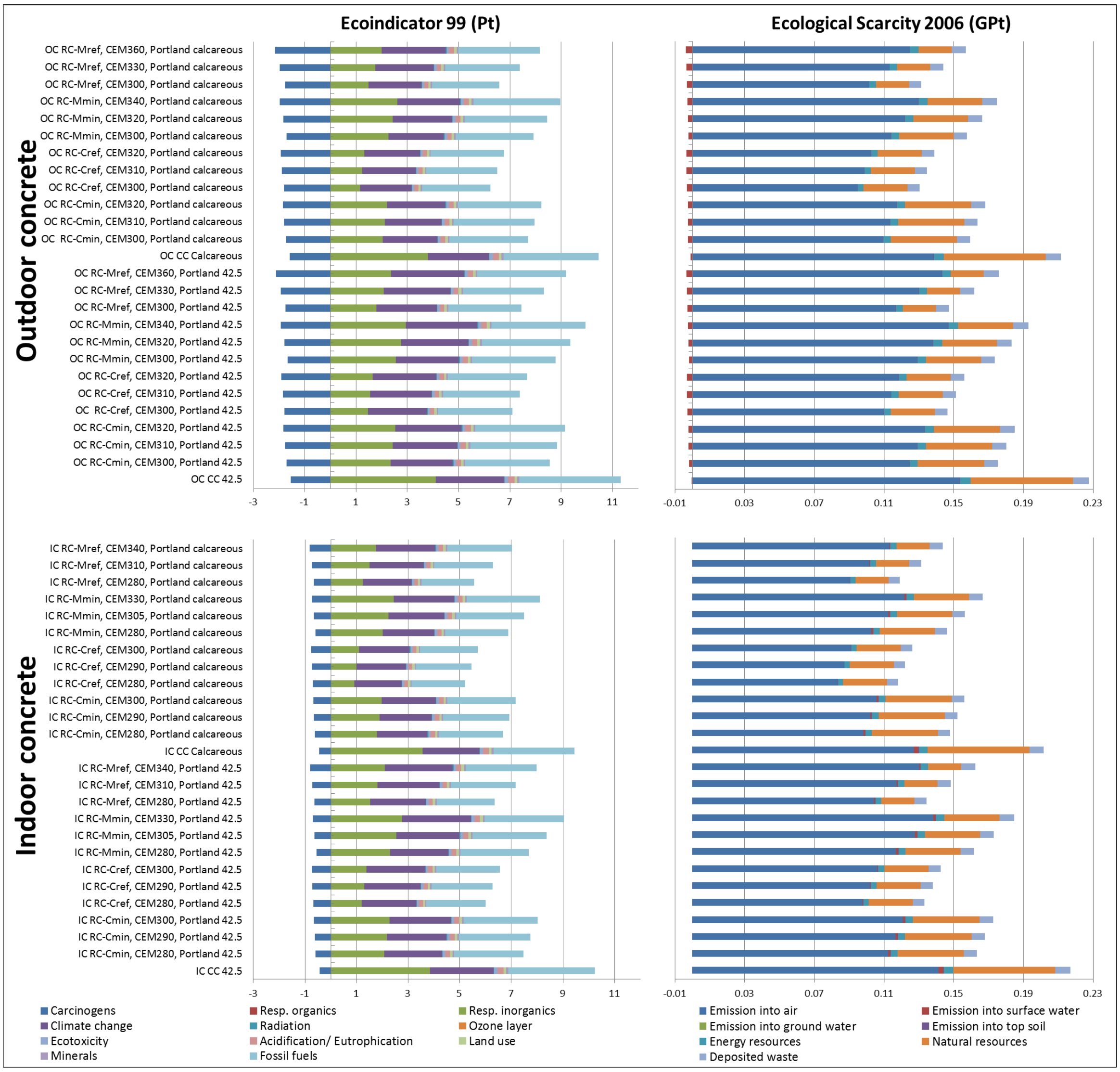

Fig. 2 Structural concrete ecoindicator 99 [Pt / m^3 concrete] and ecological scarcity 2006 [GPt / m^3 concrete] endpoint results for recycling and conventional concrete mixtures (Midpoint impacts are colour indicated for each of the two impact assessment methods)

On average RC mixtures show around 30% reduction of environmental impacts for the ecoindicator 99, ecological scarcity and ADP assessment compared to CC mixtures, while the two options are on the same level regarding GWP. This is contradictory to previous studies, which resulted in comparable or even higher environmental impacts of RC (Holcim 2010; Marinkovic et al. 2010; Weil et al. 2006). The difference might partly occur due to differences in construction practice among the countries (e.g. transport type and distances), but is more likely to be related to different system definitions, in particular to the fact that the demolition process, C&D waste transport and landfilling was largely excluded so far.

3.1.2 Lean concrete

The environmental benefits at endpoint level for recycled lean concrete mixtures were more pronounced (i.e. 88-104% for ecoindicator 99 and 80-92% for ecological scarcity 2006). The reduction is mainly due to reduced emissions into air (i.e. resp. inorganics, fossil fuels) and natural resource consumption compared to CC. In addition, lean concrete RC options show a large potential for ADP reduction, due to 100% aggregate substitution and less transport, for both recycling mixtures (e.g. 150 and 200 kg cement). Regarding GWP, the lean concrete mixtures are more balanced, although the RC options still avoid 30-40% of the CO_2 equivalents emitted (SI Fig. 2-3).

With the exception of Holcim (2010), most previous LCA studies concentrated on structural concrete applications (Weil et al. 2006; Marinkovic et al. 2010). Although not including infrastructure demolition and C&D waste transport and disposal, Holcim (2010) showed a significant environmental impact reduction for recycled lean concrete with 100% mixed rubble aggregates, reconfirmed by our results. Thus, lean RC applications show a large potential for reducing environmental impacts from concrete production on the application level even though the environmental benefits on a system level might be limited since lean concrete contributes only about 4% to building concrete applications (Lichtensteiger 2006).

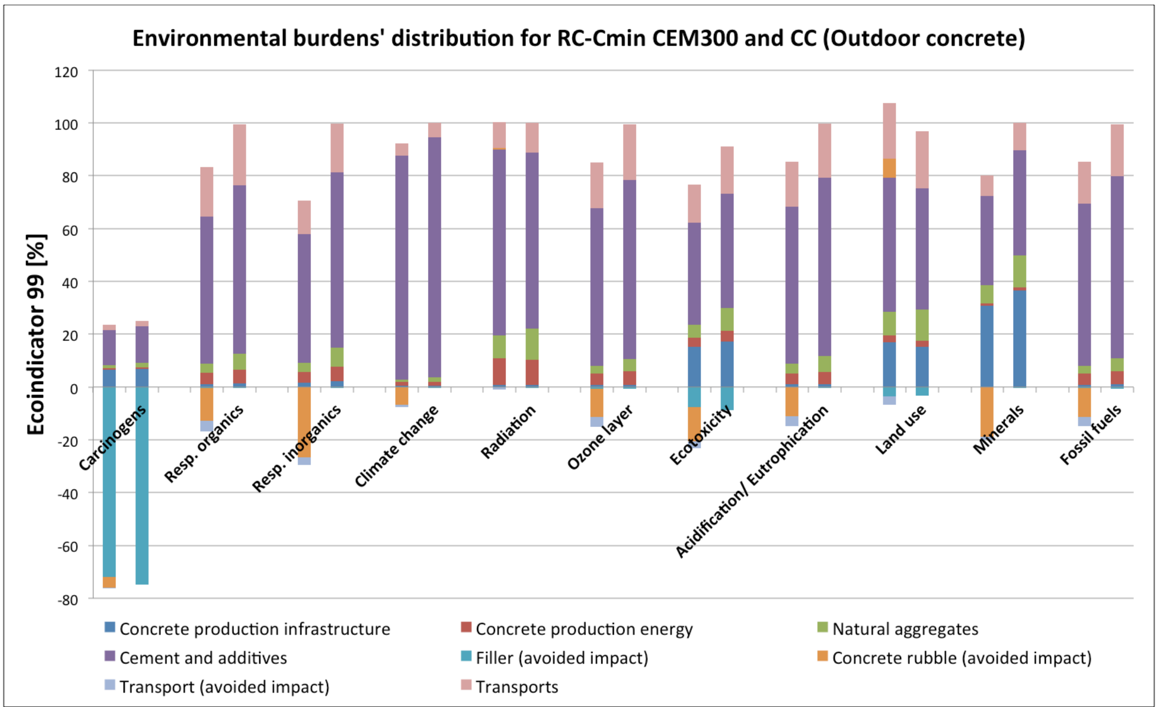

Fig. 3 Comparison of the environmental burdens' distribution of one RC-C mixture (OC RC-Cmin, CEM300, Portland 42.5) with the corresponding CC mixture (OC CC, Portland 42.5), for Ecoindicator 99 midpoints. (To eliminate the influence of the cement and transport, mixtures having the same amount and type of cement have been chosen and transport distances were kept to the reference scenario)

3.2 Contribution of concretes' life cycle stages to the environmental burden

Fig. 3 compares the contributions to the ecoindicator 99 (EI) midpoints of different life cycle stages of one RC mixture with the corresponding CC mixture (See SI Fig. 4 for ecological scarcity 2006 (EC)). Cement is the main contributor to both endpoint indicators (EI 99: 30-91%, EC 2006: 18-84%). The second largest impacts stem from transport (EI 99: 5-22%, EC 2006: 7-58%). The same is true for midpoint results with 2 exceptions: a) natural aggregates dominate EC 2006 natural resources, b) large avoided impacts for IE 99 carcinogens and EC 2006 emissions into surface water are caused by the use of fly ash as filler instead of its disposal. The main difference between the two products stems from the avoided impacts of C&D waste landfilling and recovering of steel scrap for RC (i.e. concrete rubble (avoided impacts) EI 99: 6-26%, EC 2006: 2 - 25%). Except for EC 2006 emissions into topsoil (13%) the avoided transport impacts for RC are rather small (i.e. EI 99 <4%, EC 2006: <3%) (Fig. 3). Corresponding to previous studies (Marinkovic et al. 2010; Holcim 2010; Weil et al. 2006) cement and transport were identified as the main contributor to environmental impacts of concrete. However the difference between RC and CC impacts is mainly due to the avoided impacts from C&D waste transport and landfilling and those of steel scrap recovery. This confirms that the unfavourable results for RC in previous studies are due to excluding the benefits from co-products of the recycling process.

3.3 Sensitivity to cement type and content

We analysed the sensitivity of global warming potential (GWP 100y shows the most unfavourable results for RC) to different cement types and additional amounts of cement for the RC mixtures for outdoor concrete applications. As seen above, concrete mixtures with Portland 42.5 cement show higher (12-15%) global warming potential than mixtures with Portland calcareous cement. For RC-M mixtures the amount of additional cement, for which RC-M and CC have equal GWP, is in the range of the mixtures analysed (i.e. for RC-Mmin at 24kg, for RC-Mref at 36kg). For the RC-C mixtures these points are slightly higher (i.e. for RC-Cmin at 28kg, for RC-Cref at 42kg) but outside the range of analysed market mixtures (Fig. 4 and SI Fig. 5). The additional amount of cement needed for RC is key for its environmental performance. The impact comparison with the rather unfavourable GWP shows that limiting the additional cement to about 10% compared to the amount used in CC keeps the impacts comparable to CC. This is in line with the recommendation of previous studies (Weil et al. 2006; Marinkovic et al. 2010; Holcim 2010) to limit the additional cement content for RC.

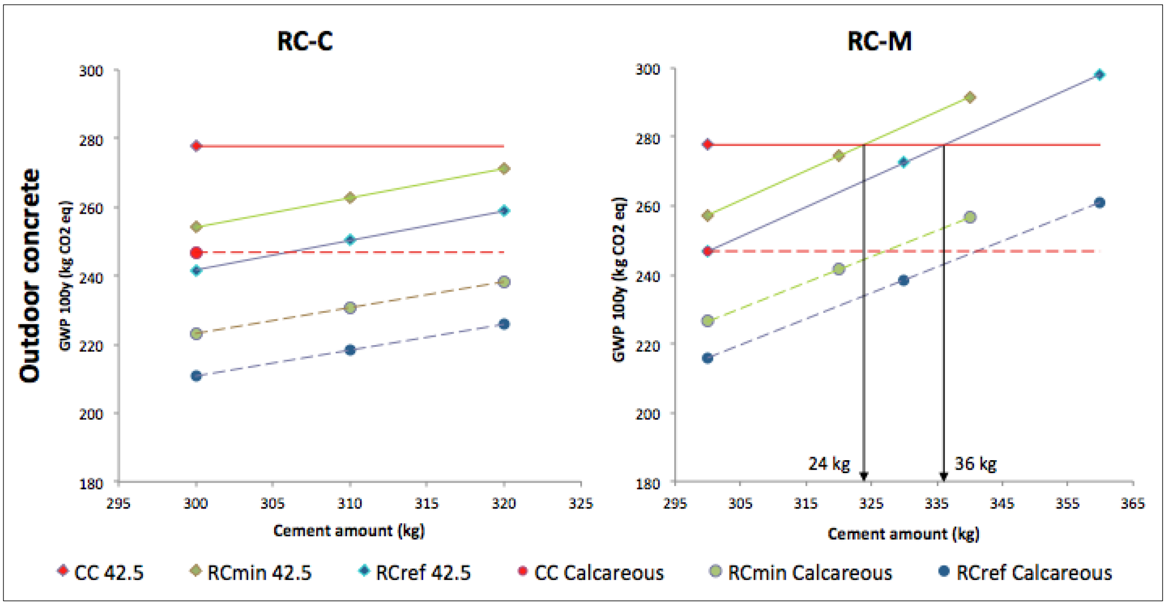

Fig. 4 Outdoor concretes' GWP [kg CO_2 eq / m^3 concrete] sensitivity to additional cement amount for recycling concrete (RC) (solid lines and rhomboid markers indicate concrete mixtures with Portland cement 42.5 and dotted lines and circled markers indicate concrete with calcareous cement)

3.4 C&D waste composition sensitivity

Although the overall assessment is dominated by cement related impacts, the main difference in the comparison between RC and CC origins from the avoided burdens of C&D waste treatment. A high share of the RC benefits is caused by the iron scrap substitution (SI Fig. 6). Thus, the sensitivity of the assumption of 70% reinforced concrete in the C&D waste concrete fraction needs to be assessed. Comparative results do not change drastically with lower reinforced concrete shares in the C&D waste concrete fraction (SI Fig. 7). Except for GWP all RC mixtures indicators show lower environmental impacts than CC, even without any avoided burdens considered for additional iron scrap recovery. Furthermore, the question as to whether it would be more beneficial to extract iron from C&D waste and dispose of the residual inert waste instead of reusing it as aggregate was investigated. SI Fig. 8 shows that this is not the case for any indicator.

3.5 The effect of additional transport distances

In the previous results the comparisons have been made based on the reference transport distance scenario (SI Table 4), representing the mean distances for Switzerland. Although concrete production is a rather local business, transport distances vary from project to project. In the best-case scenario for RC mixtures, they might be 50km (~100tkm/m^3) shorter, and in the worst-case scenario 50km (~100tkm/m^3) longer. Thus, we analysed the effect of additional lorry transport distances [ton kilometre] for RC-C outdoor concrete applications in comparison with CC (Portland 42.5 cement) (Fig. 5).

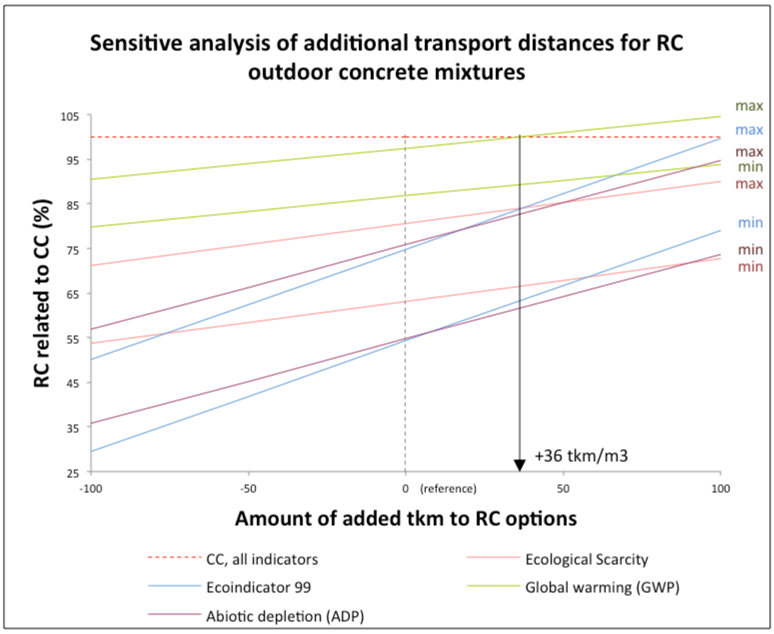

Fig. 5 Sensitive analysis of additional the transport distances for RC-C options in relation to CC for outdoor concrete (OC RC-Cmin CEM320 (max) and OC RC-Cref CEM300 (min) mixtures showed maximum and minimum values)

For the reference transport distances all RC-C mixtures have lower environmental impacts than CC for all indicators. The worst RC-C mixture has equal GWP at 36 additional ton kilometre transports for the recycling concrete. At 100 additional ton kilometre for recycling concrete only two indicators (i.e. GWP and Ecoindicator 99) are above CC for the worst RC-C mixture. ADP and

EI 99 impacts increase strongly with additional transport distances while GWP and ES 2006 results are less sensitive to additional transports. This is due to the relatively shares of transport for the particular indicators (e.g. climate change and fossil fuels in Fig. 3).

3.6 Potential of and limitation to the approach

The difference in the main result (i.e. environmental benefits of RC) compared with previous studies (Weil et al. 2006; Marinkovic et al. 2010; Holcim 2010) is explained mainly by their exclusion of co-products of C&D waste treatment. This demonstrates the importance of the consideration of co-products in the recycling processes. However, caution is recommended when generalizing the results since the study is limited to the Swiss context. Construction is a rather local business and mixtures as well as transport distances might vary in other countries. Further, the sensitivity to additional cement content suggests that mixtures with higher aggregates substitution shares and, consequently higher additional cement content might be less environmental friendly.

4 Conclusion and outlook

While previous studies showed equal or even higher environmental impacts of RC compared to CC, this study demonstrated that RC reduces the environmental impacts to about 70% of the CC impacts if co-products from the recycling process are not excluded from the scope. Cement production is still the main contributor, but considering benefits from recovered steel scrap, avoided transport of C&D waste to the deposition site, and avoided impacts of C&D waste disposal, shifts the balance in favour of RC. Global warming potential shows the smallest differences between CC and RC. Nevertheless, limiting the additional amount of cement used for RC to about 10% keeps the impact in a comparable range. While C&D waste composition has little influence on the results, additional transport for RC above 15 km starts to shift the balance again for GWP. C&D waste reuse in high-grade structural concrete applications has not only the potential to conserve natural gravel resources and limit waste streams to landfills but also to mitigate wider environmental impacts.

Acknowledgements:
The authors thank H. Eberhard, F. Gschösser, S. Rubli and M. Strauss for their support, time and knowledge; Ruairi Revell for editing the text; and FEDRO (Swiss Federal Roads Office), FOEN (Federal Office for the Environment), AWEL (Amt für Abfall, Wasser, Energie und Luft) environmental agency of canton Zurich, AHB (Amt für Hochbauten) office for structural engineering of the City of Zurich, and Eberhard Recycling AG for funding the study.

References

Bergsdal H, Brattebo H, Bohne RA, Mueller DB (2007) Dynamic material flow analysis for Norway's dwelling stock. Build Res Informat 35 (5):557-570

Blum A, Stutzriemer S (2007) Recycled construction minerals for urban infrastructure in Germany: non-technical issues. Miner Energ (3-4):148-158

Cabral A, Schalch V, Carpena D, Duarte J (2010) Mechanical properties modeling of recycled aggregate concrete. Constr Build Mater 24:421–430

Cemsuisse (2011) Jahresbericht 2011; Kennzahlen [Annual report 2011; operation figures]. Cemsuisse, Verband der Schweizerischen Cementindiustrie [Swiss cement production association], Bern

CRB (2011) Normpositionenkatalog (NPK). Standards für das Bauwesen (CRB). http://www.crb.ch/crbOnline/CRB-Standards/Normpositionen.html. Accessed 13.12.2011 2011

Doka G (2009) Life Cycle Inventories of Waste Treatment Services. Final report ecoinvent v2.1 No. 13. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

Duran X, Lenihan H, O'Regan B (2006) A model for assessing the economic viability of construction and demolition waste recycling - the case of Ireland. Resour Conserv Recycl 46 (3):302-320

Eberhard H (2011) Phone interview to concrete composition and recycling concrete mixtures. Eberhard Recycling AG, Zürich

EC (2008) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste

Eurostat (2009) Generation of waste, total arising and by selected activities for 2008.

FOEN (2001) Bauabfälle Schweiz - Mengen, Perspektiven und Entsorgungswege. Band 1: Kennwerte [Construction and demolition waste in Switzerland - amounts, perspectives and disposal routes. Volume 1: Statistical values]. Umwelt-Materialien, vol 131. Federal Office for the Environment (FOEN), Bern

FOEN (2005) An overview on waste amounts and recycling in 2004. Federal Office for the Environment (FOEN), Bern

FOEN (2006) Richtlinie für die Verwertung mineralischer Bauabfälle (Ausbauasphalt, Strassenaufbruch, Betonabbruch, Mischabbruch) [Directive for the reuse of construction and demolition waste]. Umwelt-Vollzug, vol 0631. Federal Office for the Environment (FOEN), Bern

FOEN (2010) Total quantities of waste for 2009, including recycled waste. Federal Office for the Environment (FOEN), Bern

Fonseca N, de Brito J, Evangelista L (2011) The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste. Cement Concrete Comp 33:637 – 643

FSO (2010) Material flow accounts - Growth in society's stock of materials. Environmental Accounts. Federal statistical Office (FSO), Neuchâtel

Gschösser F (2011) Phone interview to mean transport distances. Zürich

Hächler K, Frei P (2005) Herstellung von Recyclingbaustoffen - ein ökologische und ökonomische Bewertung. Semesterarbeit, ETH Zürich, Zürich

Hao JL, Hills MJ, Huang T (2007) A simulation model using system dynamic method for construction and demolition waste management in Hong Kong. Constr Innov 7 (1):7-21

Hashimoto S, Tanikawa H, Moriguchi Y (2007) Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. Waste Manage 27:1725-1738

Hiete M, Stengel J, Ludwig J, Schultmann F (2011) Matching construction and demolition waste supply to recycling demand: a regional management chain mode. Build Res Informat 39 (4):333 – 351

Hoffmann C, Jacobs F (2007) Recyclingbeton aus Beton- und Mischabbruchgranulat [Recycling concrete with concrete waste and mixed rubble as aggregates]. Material Science and Technology (EMPA), Abteilung Beton/Bauchemie und TFB, Technische Forschung und Beratung für Zement und Beton, Wildegg, Dübendorf

Hofmann W, Patt B (2006) Konstruktionen aus Mischabbruch [Structural concrete with mixed rubble aggregates]. tec21; Die Fachzeitschrift für Architektur, Ingenieurwesen und Umwelt 10:8-10

Holcim (2010) Oekobilanzen rezyklierter Gesteinskörnung für Beton [LCA of recycled concrete aggregates]. Holcim, Zurich

ISO (2005) ISO/TC 71 - Business Plan. Concrete, Reinforced Concrete and Prestressed Concrete. International Organization for Standarization (ISO), Geneva

ISO (2006) ISO 14044; Environmental management - Life cycle assessment - Principals and framework. vol ISO 14044, 2 edn. ISO,

KBOB (2007) Beton aus recyclierter Gesteinskörnung [Concrete with recycled aggregates]. Empfehlung für nachhaltiges Bauen vol 2. Koordination der Bau und Liegenschaftsorgane des Bundes (KBOB), Bern

Kellenberger D, Althaus H-J, Künniger T, Lehmann M, Jungbluth N, Thalmann P (2007) Life Cycle Inventories of Building Products. Final report ecoinvent v2.0 No. 7. Swiss Centre for Life Cycle Inventories, Duebendorf, CH

Knoeri C, Binder CR, Althaus HJ (2011) Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials. Resour Conserv Recy 55 (11):1039-1050

Künniger T, Werner F, Richter K (2001) Ökologische Bewertung von Kies, Zement und Beton in der Schweiz (Kurzfassung) [Ecological assessment of gravel, cement and concrete made in Switzerland]. Research report 115/45. Material Science and Technology (EMPA), Dübendorf, Switzerland

Lawson N, Douglas I, Garvin S, McGrath C, Manning D, Jonathan V (2001) Recycling construction and demolition wastes - a UK perspective. Environ Manage Health 12 (2):146 - 157

Li X (2008) Recycling and reuse of waste concrete in China: Part I. Material behaviour of recycled aggregate concrete. Resour Conserv Recy 53 (1-2):36-44

Lichtensteiger T (2006) Bauwerke als Ressourcennutzer und Ressourcenspender, in der langfristigen Entwicklung urbaner Systeme; Ein Beitrag zur Exploration urbaner Lagerstätten [Buildings as resource consumer and source in a long term perspective of urban systems; a contribution to urban stock exploration]. vdf Hochschulverlag AG an der ETH Zürich, Zürich

Limbachiya MC, Marrocchino E, Koulouris A (2007) Chemical-mineralogical characterisation of coarse recycled concrete aggregate. Waste Manage 27 (2):201-208

Marinkovic S, Radonjanin V, Malesev M, Ignjatovic I (2010) Comparative environmental assessment of natural and recycled aggregate concrete. Waste Manage 30 (11):2255-2264

Mercante I, Bovea M, Ibáñez-Forés V, Arena A (2011) Life cycle assessment of construction and demolition waste management systems: a Spanish case study. Int J Life Cycle Assess 17 (2):232-241

Minergie V (2007) Nutzungsreglement des Produkts Minergie-P.

Muller DB (2006) Stock dynamics for forecasting material flows - Case study for housing in The Netherlands. Ecol Econ 59 (1):142-156

Poon C-S, Kou S-c, Wan H-w, Etxeberria M (2009) Properties of concrete blocks prepared with low grade recycled aggregates. Waste Manage 29 (8):2369-2377

Rao A, Jha KN, Misra S (2007) Use of aggregates from recycled construction and demolition waste in concrete. Resour Conserv Recy 50 (1):71-81

Rubli S (2011) Phone interview to concrete and mixed rubble compositions. Energie- und Ressourcen-Management GMBH, Zürich

Schachermayer E, Lahner T, Brunner PH (2000) Assessment of two different separation techniques for building wastes. Waste Manage Res 18 (1):16-24

SIA (2002) Beton - Teil 1: Festlegung, Eigenschaften, Herstellung und Konformität [Concrete - Part 1: Configurations, Properties, Production and Conformity]. vol EN 206-1:2000. Schweizerischer Ingenieur- und Architektenverein (SIA), Zürich

SIA (2010) Recyclingbeton [Recycling Concrete]. vol SIA 2030, 2 edn. Schweizerischer Ingenieur und Architekten Verein (SIA), Schweizer Norm (SN),

Spoerri A, Lang DJ, Binder CR, Scholz RW (2009) Expert-based scenarios for strategic waste and resource management planning - C&D waste recycling in the Canton of Zurich, Switzerland. Resour Conserv Recy 53 (10):592-600

Strauss M (2011) Phone interview to recycling concrete mixtures. Eberhard Recycling AG, Zürich

WBCDS (2009) The Cement Sustainability Initiative - Concrete recycling. World Business Council for Sustainable Development (WBCDS), Geneva

Weil M, Jeske U, Schebek L (2006) Closed-loop recycling of construction and demolition waste in Germany in view of stricter environmental threshold values. Waste Manage Res 24 (3):197-206

Woodward R, Duffy N (2011) Cement and concrete flow analysis in a rapidly expanding economy: Ireland as a case study. Resour Conserv Recy 55:448–455

Part C – Appendix

Glossary

Civil engineering (CE) Design and construction of mainly publicly contracted works, such as roads, bridges, tunnels water and electricity supply and sewerage

Concrete strength class Comprehensive strength of a cylinder/cube after 28 days curing [N/mm²] (SIA 2002)

Recycled mineral construction materials (RMCM) are materials as defied in the Swiss directive for the reuse of mineral C&D waste (FOEN 2006): Recycled aggregates A (asphalt rubble up to 20%), recycled aggregates B, (> 80% roads debris), recycled aggregates P (> 95% roads debris), but in particular concrete mixtures containing concrete rubble or mixed rubble aggregates which are labelled as recycled concrete according to the SIA Norm 2030 (SIA 2010). These are RC-M (> 25% mixed rubble aggregates) and RC-C (>25% concrete rubble aggregates).

Structural engineering (SE) Design and construction of buildings

List of acronyms

ABM	Agent Based Modelling
AHP	Analytical Hierarchy Process
C&D waste	Construction and Demolition waste
CE	Civil Engineering
CC	Conventional Concrete
EE-IAO	Environmentally Extended Input-Output Analysis
LCA	Life Cycle Assessment
GWP	Global Warming Potential [kg CO_2 eq.]
NPK	Swiss construction sector standardization (Normpositionenkatalog)
RA	Recycled Aggregates
RC	Recycling Concrete
RMCM	Recycled Mineral Construction Materials
SE	Structural engineering

List of figures

Supporting information to publication II

Supporting information to the manuscript entitled;

Decisions on recycling: construction stakeholders' decisions regarding recycled mineral construction materials

Authors: Knoeri Christof [a,b], Binder Claudia R. [c] , Althaus Hans-Joerg [b]

[a] *Social and Industrial Ecology, Department of Geography, University of Zürich, Winterthurerstrasse 190 , CH-8057 Zürich, Switzerland, christof.knoeri@empa.ch*

[b] *Technology and Society Laboratory, Empa, Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland, hans-joerg.althaus@empa.ch*

[c] *Institute of Systems Sciences, Innovation and Sustainability Research (ISIS), University of Graz, Merangasse 18, 8010 Graz, Austria, claudia.binder@uni-graz.at*

Content

Table S 1: Sample description structural engineering

	Stakeholder group		Private awarding authorities N (50)		Public awarding authorities N (35)		Commercial awarding authorities N (41)		Architects N (54)		Engineers N (70)		Contractors N (49)		ZH, BE, VD, GE	Swiss	ZH, BE, VD, GE / Swiss
	Variable	labels [unit]	f_o	f_e	f_o	f_e	f_o	f_e	f_o		f_o		f_o		f_o	f_o	Sources
socio-demographic data	**Age**	25-29 years [%]	**0.0%**		**0.0%**		**0.0%**		**0.0%**		**4.4%**		2.2%		10.77%	9.86%	BfS (2008). Statistik des jährlichen Bevölkerungsstandes (ESPOP). Jährlich.
		30-34 years [%]	**2.2%**		**3.0%**		**2.8%**		**0.0%**		**11.1%**		4.4%		11.56%	10.44%	
		35-39 years [%]	**11.1%**		**6.1%**		**2.8%**		**13.3%**		**13.3%**		17.8%		12.87%	11.95%	
		40-44 years [%]	**17.8%**		**12.1%**		**22.2%**		**17.8%**		**4.4%**		13.3%		13.87%	13.18%	
		45-49 years [%]	**15.6%**		**12.1%**		**8.3%**		**15.6%**		**15.6%**		22.2%		12.52%	12.08%	
		50-54 years [%]	**22.2%**		**21.2%**		**16.7%**		**20.0%**		**13.3%**		13.3%		10.96%	10.57%	
		55-59 years [%]	**6.7%**		**24.2%**		**16.7%**		**8.9%**		**13.3%**		11.1%		10.22%	9.71%	
		60-64 years [%]	**6.7%**		**21.2%**		**19.4%**		**20.0%**		**13.3%**		8.9%		9.74%	9.08%	
		65-69 years [%]	**13.3%**		**0.0%**		**8.3%**		**4.4%**		**11.1%**		4.4%		7.49%	7.15%	
		70-74 years [%]	**4.4%**		**0.0%**		**2.8%**		**0.0%**		**0.0%**		4.4%		6.21%	5.97%	
	Gender	male [%]	**83%**		**91%**		**98%**		**96%**		**99%**		**98%**		49%	49%	
		female [%]	**17%**		**9%**		**2%**		**4%**		**1%**		**2%**		51%	51%	
	Education	Obligatory school [%]	**4%**		**0%**		**0%**		**0%**		**0%**		**0%**		18%	13%	BfS (2008). Schweizerische Arbeitskräfteerhebung (SAKE). Jährlich.
		Secondary degree [%]	**50%**		**69%**		**45%**		**24%**		**4%**		**57%**		48%	64%	
		Tertiary degree [%]	**42%**		**29%**		**48%**		**59%**		**93%**		**39%**		24%	23%	
		no answer [%]	**4%**		**3%**		**8%**		**17%**		**3%**		**4%**		7%	0%	
	Income	< 50'000 CHF [%]	**4%**		**3%**		**2%**		**0%**		**1%**		**0%**		16%		BfS (2008). Schweizerische Arbeitskräfteerhebung (SAKE). Jährlich. BfS (2008). Haushaltsbudgeterhebung (HABE). Jährlich.
		50'000 - 99'999 CHF [%]	**18%**		**20%**		**20%**		**25%**		**19%**		**31%**		29%		
		100'000 - 149'999 CHF [%]	**26%**		**46%**		**33%**		**29%**		**34%**		**22%**		21%		
		> 150'000 CHF [%]	**38%**		**17%**		**25%**		**13%**		**31%**		**29%**		24%		
		no answer [%]	**14%**		**14%**		**25%**		**33%**		**14%**		**18%**		11%		
spatial data	**Canton**	Zürich [%]	34%	34%	55%	41%	**49%**	45%	20%		47%		47%		41%	18%	BfS (2008). Bau- und Wohnbaustatistik. Jährlich.
		Bern [%]	36%	25%	23%	26%	**41%**	26%	35%		26%		35%		26%	11%	
		Vaud [%]	18%	27%	11%	16%	**5%**	14%	17%		18%		6%		18%	8%	
		Gèneve [%]	12%	15%	11%	17%	**5%**	14%	28%		9%		12%		15%	6%	
	Rural - urban distribution	Central urban community [%]	16%	14%	**14%**	53%	41%	43%	39%		**54%**		25%		36%	31%	
		Agglomeration community [%]	58%	57%	**49%**	36%	36%	44%	44%		**29%**		48%		47%	43%	
		Rural community [%]	26%	29%	**37%**	11%	22%	13%	17%		**17%**		27%		17%	26%	
construction data	**Type of construction**	New construction [%]	72%	64%	29%	31%	66%	69%	67%		*91%*		71%		61%	65%	
		Refurbishing [%]	28%	36%	71%	69%	34%	31%	33%		*9%*		29%		39%	35%	
	Building category	single-family house [%]	60%	94%	3%	9%	5%	58%	35%		16%		**29%**		56.25%	62.98%	BfS (2008). Bau- und Wohnbaustatistik. Jährlich.
		apartment house [%]	24%		3%		49%		19%		39%		**45%**				
		dwelling with secondary function [%]	4%		3%		12%		15%		15%		**10%**				
		building with minor residential function [%]	2%		14%		10%		7%		6%		**4%**				
		non-residential building [%]	10%	6%	71%	78%	24%	40%	24%		19%		**12%**		40.38%	33.92%	
		temporary building [%]	0%		6%		0%		0%		1%		**0%**				
		others [%]	0%	0%	0%	13%	0%	2%	0%		4%		**0%**		3.37%	3.09%	
	Building sum (contractors: contract sum)	<100'000 CHF *(<50'000 CHF)* [%]	4%		6%		0%		0%		0%		(4%)				
		100'000-499'999 CHF *(50'000-99'999 CHF)* [%]	26%		17%		5%		7%		7%		(8%)				
		500'000-999'999 CHF *(100'000 - 149'000 CHF)* [%]	37%		8%		10%		24%		9%		(33%)				
		>1'000'000 CHF *(>150'000 CHF)* [%]	31%		66%		85%		69%		80%		(53%)				
		no answer [%]	2%		3%		0%		0%		4%		(2%)				
	Building radius	25% quantile [km]		0.0		0.0		0.3		3.0		4.0		4.0			
		Median [km]	50	0.3	34 [ii]	0.3	41	0.5	53	5.0	70	10.0	49	10.0			
		75% quantile [km]		3.0		3.0		1.0		18.0		25.0		15.0			
	Construction frequency	25% quantile [number of projects / year]		0.2		0.8		0.4		3.5		8.0		5.3			
		Median [number of projects / year]	50 [i]	0.2	30	2.7	40	0.8	53	5.0	67	15.0	48	12.5			
		75% quantile [number of projects / year]		0.2		11.8		3.0		10.0		35.0		20.0			

Bold numbers indicate significant differences (Chi-Square < 0.05) from f_o (observed frequencies in the samples) to f_e (expected frequencies equal to the observed frequencies in the investigation area (ZH, BE, VD, GE) or the frequencies of investment per stakeholder group where specified).
[i] 78% (1 in the last 5 years), [ii] excluding one outlier at 300 km

Table S 2: Sample description civil engineering

	Stakeholder group		Public awarding authorities N (50)	Engineers N (42)	Contractors N (23)	ZH, BE, VD, GE	Swiss	ZH, BE, VD, GE / Swiss
	Variable	labels [unit]	f_o	f_o	f_o	$f_o = f_e$ (Sample)	f_o	Sources
sociographic data	**Age**	25-29 years [%]	**0.0%**	4.9%	0.0%	10.77%	9.86%	
		30-34 years [%]	**2.1%**	2.4%	8.7%	11.56%	10.44%	
		35-39 years [%]	**19.1%**	9.8%	4.3%	12.87%	11.95%	
		40-44 years [%]	**12.8%**	9.8%	13.0%	13.87%	13.18%	
		45-49 years [%]	**8.5%**	14.6%	13.0%	12.52%	12.08%	BfS (2008). Statistik des jährlichen Bevölkerungsstandes (ESPOP). Jährlich.
		50-54 years [%]	**10.6%**	22.0%	17.4%	10.96%	10.57%	
		55-59 years [%]	**29.8%**	17.1%	13.0%	10.22%	9.71%	
		60-64 years [%]	**17.0%**	9.8%	21.7%	9.74%	9.08%	
		65-69 years [%]	**0.0%**	9.8%	4.3%	7.49%	7.15%	
		70-74 years [%]	**0.0%**	0.0%	4.3%	6.21%	5.97%	
	Gender	male [%]	**94%**	**98%**	**96%**	49%	49%	
		female [%]	**6%**	**2%**	**4%**	51%	51%	
	Education	Obligatory school [%]	**0%**	**0%**	**0%**	18%	13%	BfS (2008). Schweizerische Arbeitskräfteerhebung (SAKE). Jährlich.
		Secondary degree [%]	**52%**	**12%**	**48%**	48%	64%	
		Tertiary degree [%]	**42%**	**83%**	**52%**	24%	23%	
		no answer [%]	**6%**	**5%**	**0%**	7%	0%	
	Income	< 50'000 CHF [%]	**0%**	**0%**	**0%**	16%		BfS (2008). Schweizerische Arbeitskräfteerhebung (SAKE). Jährlich. BfS (2008). Haushaltsbudgeterhebung (HABE). Jährlich.
		50'000 - 99'999 CHF [%]	**16%**	**19%**	**13%**	29%		
		100'000 - 149'999 CHF [%]	**54%**	**26%**	**26%**	21%		
		> 150'000 CHF [%]	**8%**	**31%**	**44%**	24%		
		no answer [%]	**22%**	**24%**	**17%**	11%		
spatial data	**Canton**	Zürich [%]	**38%**	**31%**	**44%**	41%	14%	
		Bern [%]	**46%**	**36%**	**57%**	26%	11%	
		Vaud [%]	**12%**	**31%**	**0%**	18%	7%	
		Gèneve [%]	**4%**	**2%**	**0%**	15%	4%	BfS (2008). Bau- und Wohnbaustatistik. Jährlich.
	Rural - urban distribution	Central urban community [%]	**28%**	45%	**30%**	46%	37%	
		Agglomeration community [%]	**46%**	31%	**35%**	40%	34%	
		Rural community [%]	**26%**	24%	**35%**	14%	29%	
construction related data	**Type of construction**	New construction [%]	44%	45%	65%	45%	46%	BfS (2008). Bau- und Wohnbaustatistik. Jährlich.
		Refurbishing [%]	56%	55%	35%	55%	54%	
	Building category (multiple answers possible)	Road construction – community road [%]	**38%**	**32%**	**31%**			
		Road construction – cantonal road [%]	**9%**	**9%**	**17%**	63.33%	60.42%	
		Road construction – national road [%]	**1%**	**6%**	**0%**			
		Railruad construction	**1%**	**6%**	**0%**	7.01%	6.72%	Schneider, M. and Rubli, S. (2008). Resourcenmodell mineralischer Baustoffe der Schweiz.
		Water supply and sewerage [%]	**30%**	**17%**	**25%**	20.40%	18.97%	
		Energy supply [%]	**11%**	**16%**	**11%**	3.74%	3.19%	
		Civil engineering structures – Bridge [%]	**6%**	**7%**	**11%**			
		Civil engineering structures – Tunnel [%]	**0%**	**1%**	**0%**			
		Civil engineering structures – Underpass / overbridge [%]	**1%**	**3%**	**0%**	5.52%	10.71%	
		others [%]	**3%**	**3%**	**6%**			
	Building sum (contractors: contract sum)	<100'000 CHF (<50'000 CHF) [%]	8%	0%	(0%)			
		100'000-499'999 CHF (50'000-99'999 CHF) [%]	24%	10%	(9%)			
		500'000-999'999 CHF (100'000 - 499'000 CHF) [%]	16%	21%	(21%)			
		>1'000'000 CHF (>500'000 CHF) [%]	52%	64%	(70%)			
		no answer [%]	0%	5%	(0%)			
	Building radius	25% quantile [km]	0.5	2.5	2.0			
		Median [km]	1.0	10.0	8.0			
		75% quantile [km]	3.3	20.0	23.8			
	Construction frequency	25% quantile [number of projects / year]	1.0	3.3	8.0			
		Median [number of projects / year]	2.0	10.0	12.0			
		75% quantile [number of projects / year]	6.0	15.0	15.0			

Bold numbers indicate significant differences (Chi-Square < 0.05) from f_o (observed frequencies in the samples) to f_e (expected frequencies equal to the observed frequencies in the investigation area (ZH, BE, VD, GE).

Table S 3: Stakeholders' decision criteria in SE ([1] private, [2] commercial, [3] public indicate criteria and descriptive properties appearing only for the particular awarding authority group. Sustainable construction specification (SCS); Decision criteria are listed and described according to the chronological decision interaction.)

stakeholder	**decision**	**decision criteria**	**description**
awarding authorities	*project specification (1)*	• social aspects	trends, image, social desirability [1,3], political objectives [3] regarding SCS and RMCM
		• economic aspects	expected investment and operation costs and allocated budget for SCS and RMCM
		• ecological aspects	knowledge and expectations about the ecological performance of SCS and RMCM
structural engineers	design specification (2)	• *project specification*	project specification from the awarding authorities about SCS or RMCM
		• expected costs	expected tender price of RMCM and conventional materials
	(engineers' recommendation)	• experience	experience with conventional materials and RMCM
		• laws and standards	existence of laws and standards regarding the usage of RMCM
architects	project design (3)	• *project specification*	project specification from the awarding authorities about SCS or RMCM
	(project recommendation)	• expected costs	expected tender price of RMCM and conventional materials
		• *engineers' recommendation*	recommendation of the engineers regarding the usage of RMCM
		• image	personal image of RMCM
		• aesthetical aspects	aesthetical performance of RMCM
awarding authorities	project confirmation (4)	• *project recommendation*	project recommendation of the architects regarding the usage of RMCM
		• expected costs	expected tender price of RMCM and conventional materials
	(basis for the tender documents)	• technical aspects [1,2]	knowledge and expectations about the technical performance of RMCM [1,2]
		• ecological aspects [1]	knowledge and expectations about the ecological performance of RMCM [1]
		• image [2,3]	personal image of RMCM [2,3]
		• marketability [2]	assessed marketability of buildings with RMCM [2]
		• political aspects [3]	political objectives regarding the usage of RMCM [3]
contractors	tender (5) *(leading to a submitted tender price)*	• *tender documents*	material specifications in the tender documents
		• economic aspects	raw material price and availability of conventional materials and RMCM, share of the material price on the overall tender sum
		• experience	experience with conventional materials and RMCM
		• technical aspects	technical feasibility and quality of RMCM, existence of laws and standards regarding the usage of RMCM, risk assessment and liability issues
awarding authorities	tender selection (6)	• *tender documents*	materials specified in the tender documents[1,2]
		• tender price	tender price of tenders with conventional materials and RMCM
		• technical aspects	knowledge and expectations about the technical performance of RMCM [1,2]
		• ecological aspects [1,3]	knowledge and expectations about the ecological performance of RMCM [1] ,transport distances [3], ecological management of the company [3]
		• marketability [1]	assessed marketability of buildings with RMCM [2]
		• quality management [3]	quality management of the company [3]
		• company references [3]	references and experience of the company with the particular type of project [3]
		• staff references [3]	knowledge, references and experience of the staff with the particular type of project [3]
		• education [3]	apprenticeship position offers [3]

Table S 4: Stakeholders' decision criteria in CE (Sustainable construction specification (SCS); Decision criteria are listed and described according to the chronological decision interaction.)

stakeholder	decision	decision criteria	description
awarding authorities	*project specification (1)*	• social aspects	trends, image and social desirability, political objectives regarding SCS and RMCM
		• economic aspects	expected investment and operation costs SCS and RMCM, demolition and disposal costs in the project
		• ecological aspects	knowledge and expectations about the ecological performance of SCS and RMCM
		• technical aspects	knowledge and expectations about the technical performance of SCS and RMCM
civil engineers	project design (2) *(project recommendation)*	• *project specification*	project specification from the awarding authorities about SCS or RMCM
		• expected costs	expected tender price of RMCM and conventional materials, demolition and disposal costs in the project
		• experience	experience with conventional materials and RMCM
		• laws and standards	existence of laws and standards regarding the usage of RMCM
awarding authorities	project confirmation (3) *(basis for the tender documents)*	• *project recommendation*	project recommendation of the engineers regarding the usage of RMCM
		• expected costs	expected tender price of RMCM and conventional materials
		• political aspects	political objectives regarding the usage of RMCM
		• image	personal image of RMCM
contractors	tender (4) *(leading to a submitted tender price)*	• selection criteria	predefined tender selection criteria from the awarding authorities
		• economic aspects	raw material price and availability of conventional materials and RMCM, demolition and disposal costs in the project
		• experience	experience with conventional materials and RMCM
		• technical aspects	technical feasibility and quality of RMCM, existence of laws and standards regarding the usage of RMCM, risk assessment and liability issues
		• *tender documents*	material specifications in the tender documents
awarding authorities	tender selection (5)	• *tender price*	tender price of tenders with conventional materials and RMCM
		• quality management	quality management of the company
		• company references	references and experience of the company with the particular type of project
		• staff references	knowledge, references and experience of the staff with the particular type of project
		• education	apprenticeship position offers
		• ecological aspects	transport distances, ecological management of the company

Table S 5: Stakeholders' decision alternatives/options in SE per stakeholder, decision and application (Decision alternatives are listed and described according to the chronological decision interaction; Abbreviation (ABBR))

stakeholder	decision	application	alternative	ABBR	description
awarding authorities (AA)	*project specification (1)*	(not application specific)	• Sustainable construction specification	SCS	The AA general claims for sustainable construction
			• Specify recycled mineral construction materials	RMCM	The AA specifically claims and specifies the use of RMCM
			• No sustainable construction specification	NSCS	The AA makes no specification regarding sustainable construction of RMCM
structural engineers	design specification (2) *(engineers' recommendation)*	• outside concrete	• *Conventional concrete*	CC	The engineers recommends conventional concrete for outside concrete applications
			• *Recycled concrete B*	RCB	The engineers recommends recycled concrete B for outside concrete applications
			• *Property specification*	PS	The engineers specifies properties to fulfill for outside concrete applications and does not recommend a particular material
		• inside concrete	• *Conventional concrete*	CC	The engineers recommends conventional concrete for inside concrete applications
			• *Recycled concrete M*	RCM	The engineers recommends recycled concrete M for inside concrete applications
			• *Property specification*	PS	The engineers specifies properties to fulfill for inside concrete applications and does not recommend a particular material
		• lean concrete	• *Conventional concrete*	CC	The engineers recommends conventional concrete for lean concrete applications
			• *Recycled concrete M*	RCM	The engineers recommends recycled concrete M for lean concrete applications
			• *Property specification*	PS	The engineers specifies properties to fulfill for lean concrete applications and does not recommend a particular material
architects	project design (3) *(project recommendation)*	• outside concrete	• *Conventional concrete*	CC	The architect recommends conventional concrete for outside concrete applications
			• *Recycled concrete B*	RCB	The architect recommends recycled concrete B for outside concrete applications
			• *Property specification*	PS	The architect specifies properties to fulfill for outside concrete applications and does not recommend a particular material
		• inside concrete	• *Conventional concrete*	CC	The architect recommends conventional concrete for inside concrete applications
			• *Recycled concrete M*	RCM	The architect recommends recycled concrete M for inside concrete applications
			• *Property specification*	PS	The architect specifies properties to fulfill for inside concrete applications and does not recommend a particular material
		• lean concrete	• *Conventional concrete*	CC	The architect recommends conventional concrete for lean concrete applications
			• *Recycled concrete M*	RCM	The architect recommends recycled concrete M for lean concrete applications
			• *Property specification*	PS	The architect specifies properties to fulfill for lean concrete applications and does not recommend a particular material

stakeholder	decision	• application	• alternative	ABBR	description
awarding authorities	project confirmation (4) *(basis for the tender documents)*	• outside concrete	• *Conventional concrete*	CC	The AA confirms that for outside concrete applications conventional concrete is specified in tender documents
			• *Recycled concrete B*	RCB	The AA confirms that for outside concrete applications recycled concrete B is specified in tender documents
			• *Property specification*	PS	The AA confirms that for outside concrete applications material properties are specified in tender documents
		• inside concrete	• *Conventional concrete*	CC	The AA confirms that for inside concrete applications conventional concrete is specified in tender documents
			• *Recycled concrete M*	RCM	The AA confirms that for inside concrete applications recycled concrete M is specified in tender documents
			• *Property specification*	PS	The AA confirms that for inside concrete applications material properties are specified in tender documents
		• lean concrete	• *Conventional concrete*	CC	The AA confirms that for lean concrete applications conventional concrete is specified in tender documents
			• *Recycled concrete M*	RCM	The AA confirms that for lean concrete applications recycled concrete M is specified in tender documents
			• *Property specification*	PS	The AA confirms that for lean concrete applications material properties are specified in tender documents
contractors	tender (5) *(leading to a submitted tender price)*	• outside concrete	• *Conventional concrete*	CC	The contractor submit a tender with conventional concrete for outside concrete applications
			• *Recycled concrete B*	RCB	The contractor submit a tender with recycled concrete B for outside concrete applications
		• inside concrete	• *Conventional concrete*	CC	The contractor submit a tender with conventional concrete for inside concrete applications
			• *Recycled concrete M*	RCM	The contractor submit a tender with recycled concrete M for inside concrete applications
		• lean concrete	• *Conventional concrete*	CC	The contractor submit a tender with conventional concrete for lean concrete applications
			• *Recycled concrete M*	RCM	The contractor submit a tender with recycled concrete M for lean concrete applications
awarding authorities	tender selection (6)	• outside concrete	• *Conventional concrete*	CC	The AA select a tender with conventional concrete for outside concrete applications
			• *Recycled concrete B*	RCB	The AA select a tender with recycled concrete B for outside concrete applications
		• inside concrete	• *Conventional concrete*	CC	The AA select a tender with conventional concrete for inside concrete applications
			• *Recycled concrete M*	RCM	The AA select a tender with recycled concrete M for inside concrete applications
		• lean concrete	• *Conventional concrete*	CC	The AA select a tender with conventional concrete for lean concrete applications
			• *Recycled concrete M*	RCM	The AA select a tender with recycled concrete M for lean concrete applications

Table S 6: Stakeholders' decision alternatives/options in CE per stakeholder, decision and application (Decision alternatives are listed and described according to the chronological decision interaction; Abbreviation (ABBR))

stakeholder	decision	application	alternative	ABBR	description
awarding authorities (AA)	*project specification (1)*	(not application specific)	• Sustainable construction specification	SCS	The AA general claims for sustainable construction
			• Specify recycled mineral construction materials	RMCM	The AA specifically claims and specifies the use of RMCM
			• No sustainable construction specification	NSCS	The AA makes no specification regarding sustainable construction of RMCM
civil engineers	design specification (2) *(engineers' recommendation)*	• bonded sub base	• Conventional aggregate	CA	The engineers recommends conventional aggregate for bonded sub base applications
			• Recycled aggregate P	RAP	The engineers recommends recycled aggregate P for bonded sub base applications
			• Recycled aggregate A	RAA	The engineers recommends recycled aggregate A for bonded sub base applications
			• *Property specification*	PS	The engineers specifies properties to fulfill for bonded sub base applications and does not recommend a particular material
		• unbonded sub base	• Conventional aggregate	CA	The engineers recommends conventional aggregate for unbonded sub base applications
			• Recycled aggregate B	RAB	The engineers recommends recycled aggregate B for unbonded sub base applications
			• Recycled mixed rubble aggregates	RAM	The engineers recommends recycled aggregate M for unbonded sub base applications
			• *Property specification*	PS	The engineers specifies properties to fulfill for unbonded sub base applications and does not recommend a particular material
		• lean concrete	• *Conventional concrete*	CC	The engineers recommends conventional concrete for lean concrete applications
			• *Recycled concrete B*	RCB	The engineers recommends recycled concrete B for lean concrete applications
			• *Recycled concrete M*	RCM	The engineers recommends recycled concrete M for lean concrete applications
			• *Property specification*	PS	The engineers specifies properties to fulfill for lean concrete applications and does not recommend a particular material
awarding authorities	project confirmation (3) *(basis for the tender documents)*	• bonded sub base	• Conventional aggregate	CA	The AA confirms that for bonded sub base applications conventional aggregate is specified in tender documents
			• Recycled aggregate P	RAP	The AA confirms that for bonded sub base applications recycled aggregate P is specified in tender documents
			• Recycled aggregate A	RAA	The AA confirms that for bonded sub base applications recycled aggregate A is specified in tender documents
			• *Property specification*	PS	The AA confirms that for bonded sub base applications material properties are specified in tender documents
		• unbonded sub base	• Conventional aggregate	CA	The AA confirms that for unbonded sub base applications conventional aggregate is specified in tender documents
			• Recycled aggregate B	RAB	The AA confirms that for unbonded sub base applications recycled aggregate B is specified in tender documents
			• Recycled mixed rubble aggregates	RAM	The AA confirms that for unbonded sub base applications recycled aggregate M is specified in tender documents

			• *Property specification*	PS	The AA confirms that for unbonded sub base applications material properties are specified in tender documents
		• lean concrete	• *Conventional concrete*	CC	The AA confirms that for lean concrete applications conventional concrete is specified in tender documents
			• *Recycled concrete B*	RCB	The AA confirms that for lean concrete applications recycled concrete B is specified in tender documents
			• *Recycled concrete M*	RCM	The AA confirms that for lean concrete applications recycled concrete M is specified in tender documents
			• *Property specification*	PS	The AA confirms that for lean concrete applications material properties are specified in tender documents
contractors	tender (4) *(leading to a submitted tender price)*	• bonded sub base	• Conventional aggregate	CA	The contractor submit a tender with conventional aggregate for bonded sub base applications
			• Recycled aggregate P	RAP	The contractor submit a tender with recycled aggregate P for bonded sub base applications
			• Recycled aggregate A	RAA	The contractor submit a tender with recycled aggregate A for bonded sub base applications
		• unbonded sub base	• Conventional aggregate	CA	The contractor submit a tender with conventional aggregate for unbonded sub base applications
			• Recycled aggregate B	RAB	The contractor submit a tender with recycled aggregate B for unbonded sub base applications
			• Recycled mixed rubble aggregates	RAM	The contractor submit a tender with recycled aggregate M for unbonded sub base applications
		• lean concrete	• *Conventional concrete*	CC	The contractor submit a tender with conventional concrete for lean concrete applications
			• *Recycled concrete B*	RCB	The contractor submit a tender with recycled concrete B for lean concrete applications
			• *Recycled concrete M*	RCM	The contractor submit a tender with recycled concrete M for lean concrete applications
awarding authorities	tender selection (5)	• bonded sub base	• Conventional aggregate	CA	The AA select a tender with conventional aggregate for bonded sub base applications
			• Recycled aggregate P	RAP	The AA select a tender with recycled aggregate P for bonded sub base applications
			• Recycled aggregate A	RAA	The AA select a tender with recycled aggregate A for bonded sub base applications
		• unbonded sub base	• Conventional aggregate	CA	The AA select a tender with conventional aggregate for unbonded sub base applications
			• Recycled aggregate B	RAB	The AA select a tender with recycled aggregate B for unbonded sub base applications
			• Recycled mixed rubble aggregates	RAM	The AA select a tender with recycled aggregate M for unbonded sub base applications
		• lean concrete	• *Conventional concrete*	CC	The AA select a tender with conventional concrete for lean concrete applications
			• *Recycled concrete B*	RCB	The AA select a tender with recycled concrete B for lean concrete applications
			• *Recycled concrete M*	RCM	The AA select a tender with recycled concrete M for lean concrete applications

Table S 7: Private awarding authorities' decision data in structural engineering

Decision			Alternative	Criteria		Criteria weights				Alternative weights per criteria						Alternative preference				
type	appl.	N		no.	criteria	mean	SD	sign. levels (1)		crit.	alternative	mean	SD	sign. levels (1)		alternative	mean	SD	sign. levels (1)	
Project specification	general									1	SCS	**0.49**	0.19	***	***					
											RMCM	**0.27**	0.13	***						
											NSCS	**0.25**	0.19		***					
			Sustainable construction specification (SCS)	1	Social aspects	**0.19**	0.15	***	***	2	SCS	**0.46**	0.19	***	***	SCS	**0.45**	0.15	***	***
		49	Recycled mineral construction material (RMCM)	2	Economic aspects	**0.39**	0.20	***			RMCM	**0.29**	0.16	***		RMCM	**0.30**	0.13	***	
			No sustainable construction specification (NSCS)	3	Ecological aspects	**0.42**	0.18		***		NSCS	**0.25**	0.19		***	NSCS	**0.26**	0.16		***
										3	SCS	**0.41**	0.17	***						
											RMCM	**0.33**	0.16							
											NSCS	**0.26**	0.17	***						
	External concrete									1	CC	**0.32**	0.21							
											RCB	**0.26**	0.18	**						
											PS	**0.42**	0.19	**						
										2	CC	**0.31**	0.19							
			Conventional concrete (CC)	1	Project recommendation	**0.33**	0.19		**		RCB	**0.26**	0.17	**		CC	0.33	0.19		
		35	Recycling concrete B (RCB)	2	Expected costs	**0.22**	0.14				PS	**0.43**	0.20	**		RCB	0.27	0.16		
			Property specification (PS)	3	Technical aspects	**0.26**	0.14			3	CC	**0.37**	0.22	**		PS	0.40	0.18		
				4	Ecological aspects	**0.18**	0.14		**		RCB	**0.23**	0.16	**	***					
											PS	**0.40**	0.22		***					
										4	CC	0.25	0.19							
											RCB	0.39	0.22							
											PS	0.36	0.18							
Project confirmation	Internal concrete									1	CC	0.34	0.21							
											RCM	0.29	0.19							
											PS	0.38	0.20							
										2	CC	**0.34**	0.20							
			Conventional concrete (CC)	1	Project recommendation	0.31	0.19				RCM	**0.25**	0.17	**		CC	0.34	0.19		
		34	Recycling concrete M (RCM)	2	Expected costs	0.24	0.14				PS	**0.41**	0.19	**		RCM	0.29	0.16		
			Property specification (PS)	3	Technical aspects	0.25	0.11			3	CC	0.35	0.21			PS	0.37	0.17		
				4	Ecological aspects	0.20	0.13				RCM	0.27	0.17							
											PS	0.39	0.20							
										4	CC	0.27	0.19							
											RCM	0.38	0.22							
											PS	0.34	0.18							
	Lean concrete									1	CC	0.31	0.19							
											RCM	0.30	0.19							
											PS	0.39	0.18							
										2	CC	0.34	0.17							
			Conventional concrete (CC)	1	Project recommendation	**0.35**	0.18	*	**		RCM	0.27	0.16			CC	0.32	0.16		
		34	Recycling concrete M (RCM)	2	Expected costs	**0.22**	0.13	*			PS	0.39	0.18			RCM	0.30	0.17		
			Property specification (PS)	3	Technical aspects	**0.25**	0.12			3	CC	0.36	0.19			PS	0.38	0.16		
				4	Ecological aspects	**0.19**	0.13		**		RCM	0.26	0.17							
											PS	0.37	0.17							
										4	CC	**0.24**	0.16	**	**					
											RCM	**0.41**	0.22	**						
											PS	**0.35**	0.16		**					
Tender selection	External concrete			1	Tender documents	0.21	0.15			3	CC	**0.61**	0.23	***						
		33	Conventional concrete (CC)	2	Tender price	0.26	0.14				RCB	**0.39**	0.23	***						
			Recycling concrete B (RCB)	3	Technical aspects (2)	0.32	0.17			4	CC	**0.40**	0.25	**						
				4	Ecological aspects	0.21	0.16				RCB	**0.60**	0.25	**						
	Internal concrete			1	Tender documents	0.20	0.14			3	CC	**0.64**	0.23	***						
		33	Conventional concrete (CC)	2	Tender price	0.27	0.13				RCM	**0.36**	0.23	***						
			Recycling concrete M (RCM)	3	Technical aspects (2)	0.30	0.15			4	CC	0.43	0.26							
				4	Ecological aspects	0.22	0.17				RCM	0.57	0.26							
	Lean concrete			1	Tender documents	0.21	0.13			3	CC	**0.59**	0.24	**						
		33	Conventional concrete (CC)	2	Tender price	0.28	0.13				RCM	**0.41**	0.24	**						
			Recycling concrete M (RCM)	3	Technical aspects (2)	0.29	0.13			4	CC	**0.40**	0.24	**						
				4	Ecological aspects	0.23	0.16				RCM	**0.60**	0.24	**						

Bold numbers indicate significant (GLM repeated measures with the Huynh-Feldt ε-correction (α = 0.05)) differences among the criteria/alternatives.
(1) Bonferoni corrected significance levels of paired t-tests (* 0.10, ** 0.05, *** 0.01) between the indicated criteria/alternatives.
(2) Technical aspects show a slightly higher criteria weight in all three applications which is not significant with the conservative Bonferoni correction.

Table S 8: Commercial awarding authorities’ decision data in structural engineering

KBH

Decision			Alternative	Criteria		Criteria weights					Alternative weights per criteria						Alternative preference				
type	appl.	N		no.	criteria	mean	SD	sign. levels [(1)]			crit.	alternative	mean	SD	sign. levels [(1)]		alternative	mean	SD	sign. levels [(1)]	
Project specification	general										**1**	SCS	**0.52**	0.17	***	***					
												RMCM	**0.27**	0.13	***						
												NSCS	**0.20**	0.18		***					
			Sustainable construction specification (SCS)	**1**	Social aspects	**0.29**	0.19	*			**2**	SCS	**0.48**	0.19	***	***	SCS	**0.50**	0.17	***	***
		41	Recycled mineral construction material (RMCM)	**2**	Economic aspects	**0.41**	0.18	*	**			RMCM	**0.28**	0.15	***		RMCM	**0.28**	0.12	***	
			No sustainable construction specification (NSCS)	**3**	Ecological aspects	**0.29**	0.17		**			NSCS	**0.24**	0.20		***	NSCS	**0.22**	0.17		***
											3	SCS	**0.49**	0.19	***	***					
												RMCM	**0.30**	0.13	***						
												NSCS	**0.22**	0.19		***					
Project confirmation	External concrete										**1**	CC	**0.58**	0.50	***						
												RCB	**0.10**	0.30	***						
												PS	**0.32**	0.48							
											2	CC	**0.32**	0.19							
												RCB	**0.25**	0.16	***						
				1	Project recommendation	**0.20**	0.14					PS	**0.43**	0.20	***						
			Conventional concrete (CC)	2	Expected costs	**0.20**	0.11				**3**	CC	**0.45**	0.17	***		CC	**0.42**	0.21	***	
		31	Recycling concrete B (RCB)	3	Technical aspects	**0.23**	0.11	***				RCB	**0.21**	0.17	***	**	RCB	**0.22**	0.17	***	***
			Property specification (PS)	4	Image	**0.13**	0.08	***	***			PS	**0.34**	0.17		**	PS	**0.36**	0.15		***
				5	Marketability	**0.25**	0.13		***		**4**	CC	0.35	0.20							
												RCM	0.32	0.21	**						
												PS	0.33	0.14	**						
											5	CC	0.37	0.19							
												RCB	0.28	0.18							
												PS	0.35	0.15							
	Internal concrete										**1**	CC	**0.55**	0.51	***						
												RCM	**0.10**	0.30	***	*					
												PS	**0.35**	0.49		*					
											2	CC	**0.35**	0.17							
												RCM	**0.24**	0.16	**						
				1	Project recommendation	**0.18**	0.15					PS	**0.41**	0.20	**						
			Conventional concrete (CC)	2	Expected costs	**0.22**	0.12	**			**3**	CC	**0.44**	0.18	***		CC	**0.42**	0.19	***	
		31	Recycling concrete M (RCM)	3	Technical aspects	**0.23**	0.10		***			RCM	**0.22**	0.15	***	*	RCM	**0.21**	0.16	***	***
			Property specification (PS)	4	Image	**0.12**	0.08	**	***	***		PS	**0.34**	0.17		*	PS	**0.37**	0.17		***
				5	Marketability	**0.25**	0.12			***	**4**	CC	0.34	0.19							
												RCM	0.30	0.22							
												PS	0.36	0.16							
											5	CC	**0.44**	0.17	***	**					
												RCM	**0.25**	0.17	***						
												PS	**0.31**	0.12		**					
	Lean concrete										**1**	CC	**0.65**	0.49	***						
												RCM	**0.00**	0.00	***	***					
												PS	**0.35**	0.49		***					
											2	CC	**0.33**	0.16							
												RCM	**0.25**	0.17	**						
				1	Project recommendation	**0.19**	0.15					PS	**0.42**	0.19	**						
			Conventional concrete (CC)	2	Expected costs	**0.24**	0.14	***			**3**	CC	**0.42**	0.17	***		CC	**0.43**	0.19	***	
		31	Recycling concrete M (RCM)	3	Technical aspects	**0.24**	0.09		***			RCM	**0.22**	0.15	***	**	RCM	**0.19**	0.11	***	***
			Property specification (PS)	4	Image	**0.12**	0.08	***	***	***		PS	**0.36**	0.17		**	PS	**0.38**	0.15		***
				5	Marketability	**0.21**	0.12			***	**4**	CC	0.37	0.19							
												RCM	0.31	0.20							
												PS	0.33	0.15							
											5	CC	0.39	0.18							
												RCM	0.27	0.17							
												PS	0.34	0.15							
Tender selection	External concrete			1	Tender documents	**0.16**	0.15	*	***		**3**	CC	**0.70**	0.16	***						
		31	Conventional concrete (CC)	2	Tender price	**0.28**	0.14	*				RCB	**0.30**	0.16	***						
			Recycling concrete B (RCB)	3	Technical aspects	**0.34**	0.12		***	***	**4**	CC	**0.62**	0.18	***						
				4	Marketability	**0.22**	0.12			***		RCB	**0.38**	0.18	***						
	Internal concrete			1	Tender documents	**0.17**	0.15	***			**3**	CC	**0.70**	0.16	***						
		31	Conventional concrete (CC)	2	Tender price	**0.27**	0.14	***				RCM	**0.30**	0.16	***						
			Recycling concrete M (RCM)	3	Technical aspects	**0.33**	0.13		**		**4**	CC	**0.63**	0.17	***						
				4	Marketability	**0.22**	0.11		**			RCM	**0.37**	0.17	***						
	Lean concrete			1	Tender documents	**0.16**	0.14	**	***		**3**	CC	**0.69**	0.16	***						
		31	Conventional concrete (CC)	2	Tender price	**0.29**	0.15	**				RCM	**0.31**	0.16	***						
			Recycling concrete M (RCM)	3	Technical aspects	**0.32**	0.12		***	*	**4**	CC	**0.58**	0.17	**						
				4	Marketability	**0.23**	0.13			*		RCM	**0.42**	0.17	**						

Bold numbers indicate significant (GLM repeated measures with the Huynh-Feldt ε-correction (α = 0.05)) differences among the criteria/alternatives.
[(1)] Bonferoni corrected significance levels of paired t-tests (* 0.10, ** 0.05, *** 0.01) between the indicated criteria/alternatives.

Table S 9: Public awarding authorities' decision data in structural engineering

Decision			Alternative	Criteria		Criteria weights			Alternative weights per criteria							Alternative preference					
type	appl.	N		no.	criteria	mean	SD	sign. levels [1]	crit.	alternative	mean	SD	sign. levels [1]			alternative	mean	SD	sign. levels [1]		
Project specification	general								1	SCS	**0.50**	0.18	***	***							
										RMCM	**0.30**	0.12	***		*						
										NSCS	**0.20**	0.18		***	*						
			Sustainable construction specification (SCS)	1	Social aspects	**0.26**	0.16	**	2	SCS	**0.47**	0.18	***	***		SCS	**0.47**	0.14	***	***	
		35	Recycled mineral construction material (RMCM)	2	Economic aspects	**0.39**	0.17	**		RMCM	**0.29**	0.11	***			RMCM	**0.32**	0.09	***		***
			No sustainable construction specification (NSCS)	3	Ecological aspects	**0.36**	0.16			NSCS	**0.24**	0.20		***		NSCS	**0.21**	0.13		***	***
									3	SCS	**0.46**	0.17	**	***							
										RMCM	**0.34**	0.14	**		***						
										NSCS	**0.21**	0.16		***	***						
Project confirmation	External concrete								1	CC	**0.34**	0.48	**								
										RCB	**0.06**	0.24	**	***							
										PS	**0.60**	0.50		***							
									2	CC	**0.44**	0.18	***	*							
			Conventional concrete (CC)	1	Project recommendation [2]	0.30	0.16			RCB	**0.25**	0.13	***			CC	**0.39**	0.22	**		
		35	Recycling concrete B (RCB)	2	Expected costs	0.27	0.14			PS	**0.31**	0.14		*		RCB	**0.24**	0.14	**	**	
			Property specification (PS)	3	Political aspects	0.21	0.11		3	CC	0.29	0.15				PS	**0.37**	0.19		**	
				4	Image	0.22	0.12			RCB	0.37	0.13									
										PS	0.34	0.13									
									4	CC	0.32	0.18									
										RCB	0.35	0.17									
										PS	0.32	0.12									
	Internal concrete								1	CC	**0.34**	0.48	**								
										RCM	**0.06**	0.24	**	***							
										Ps	**0.60**	0.50		***							
									2	CC	**0.47**	0.21	***	***							
			Conventional concrete (CC)	1	Project recommendation [2]	0.29	0.17			RCM	**0.25**	0.13	***			CC	**0.39**	0.22	***		
		35	Recycling concrete M (RCM)	2	Expected costs [2]	0.29	0.16			Ps	**0.31**	0.14		***		RCM	**0.22**	0.10	***	***	
			Property specification (PS)	3	Political aspects	0.22	0.10		3	CC	0.30	0.14				PS	**0.39**	0.19		***	
				4	Image	0.20	0.11			RCM	0.34	0.13									
										PS	0.36	0.14									
									4	CC	0.34	0.19									
										RCM	0.33	0.15									
										PS	0.33	0.15									
	Lean concrete								1	CC	**0.23**	0.43	***								
										RCM	**0.09**	0.28		***							
										PS	**0.69**	0.47	***	***							
									2	CC	**0.41**	0.17	***								
			Conventional concrete (CC)	1	Project recommendation	0.26	0.14			RCM	**0.27**	0.12	***			CC	**0.34**	0.18	*		
		35	Recycling concrete M (RCM)	2	Expected costs	0.29	0.16			PS	**0.32**	0.15				RCM	**0.25**	0.10	*	***	
			Property specification (PS)	3	Political aspects	0.24	0.11		3	CC	0.31	0.13				PS	**0.40**	0.18		***	
				4	Image	0.21	0.10			RCM	0.37	0.13									
										PS	0.32	0.13									
									4	CC	0.33	0.17	**	*							
										RCM	0.36	0.15	**								
										PS	0.31	0.14		*							

Bold numbers indicate significant (GLM repeated measures with the Huynh-Feldt ε-correction (α = 0.05)) differences among the criteria/alternatives.
[1] Bonferoni corrected significance levels of paired t-tests (* 0.10, ** 0.05, *** 0.01) between the indicated criteria/alternatives.
[2] Slightly higher criteria weights which are not significant with the conservative Bonferoni correction.

Table S 10: Engineers' decision data in structural engineering

Decision type	Decision appl.	N	Alternative	Criteria no.	Criteria	Criteria weights mean	SD	sign. levels (1)			Alternative preference alternative	mean	SD	sign. levels (1)			
Project recommendation	Bound sub-base	39	Conventional aggregate (CA)	1	Project specification	**0.13**	0.12	***	***	***	CA	**0.32**	0.16	***			
			Recycled aggregate P (RAP)	2	Expected costs	**0.26**	0.15	***			RAP	**0.26**	0.11		**		
			Recycled aggregate A (RAA)	3	Experience	**0.27**	0.11		***		RAA	**0.19**	0.09	***	**		
			Property specification (PS)	4	Law and standards	**0.34**	0.16			***	PS	**0.24**	0.10				
	Unbound sub-base	39	Conventional aggregate (CA)	1	Project specification	**0.13**	0.13	***	***	***	CA	**0.35**	0.17	*	***	***	
			Recycled aggregate B (RAB)	2	Expected costs	**0.26**	0.14	***			RAB	**0.25**	0.10	*			***
			Recycled mixed rubble aggregate (RAM)	3	Experience	**0.27**	0.11		***		RAM	**0.19**	0.07		***		***
			Property specification (PS)	4	Law and standards	**0.33**	0.16			***	PS	**0.21**	0.10			***	
	Lean concrete	39	Conventional concrete (CC)	1	Project specification	**0.15**	0.14	**	***	***	CC	**0.31**	0.17	**			
			Recycling concrete M (RCM)	2	Expected costs	**0.26**	0.14	**			RCM	**0.23**	0.10		*		
			Recycling concrete B (RCB)	3	Experience	**0.28**	0.13		***		RCB	**0.27**	0.08		*	***	
			Property specification (PS)	4	Law and standards	**0.31**	0.17			***	PS	**0.19**	0.09	**		***	

appl.	Alternative weights per criteria crit.	alternative	mean	SD	sign. levels (1)				
Bound sub-base	1	CA	0.25	0.20					
		RAP	0.28	0.13					
		RAA	0.22	0.12					
		PS	0.25	0.15					
	2	CA	0.19	0.18					
		RAP	0.29	0.13					
		RAA	0.26	0.11					
		PS	0.27	0.15					
	3	CA	**0.37**	0.17	*	***	***		
		RAP	**0.26**	0.13	*			***	
		RAA	**0.16**	0.10		***		***	
		PS	**0.22**	0.13			***		
	4	CA	**0.39**	0.19	***	***	***		
		RAP	**0.23**	0.11	***				
		RAA	**0.17**	0.09		***			
		PS	**0.21**	0.10			***		
Unbound sub-base	1	CA	**0.28**	0.19					
		RAB	**0.30**	0.12	***	**			
		RAM	**0.21**	0.11	***				
		PS	**0.21**	0.12		**			
	2	CA	0.23	0.20					
		RAB	0.25	0.11					
		RAM	0.26	0.11					
		PS	0.26	0.14					
	3	CA	**0.39**	0.18	***	***	***		
		RAB	**0.24**	0.11	***			**	
		RAM	**0.17**	0.09		***		**	
		PS	**0.21**	0.12			***		
	4	CA	**0.40**	0.18	***	***	***		
		RAB	**0.24**	0.10	***			***	*
		RAM	**0.17**	0.08		***		***	
		PS	**0.19**	0.09			***		*
Lean concrete	1	CC	**0.26**	0.20					
		RCM	**0.25**	0.12	*				
		RCB	**0.31**	0.11	*	***			
		PS	**0.18**	0.11		***			
	2	CC	0.21	0.18					
		RCM	0.29	0.12					
		RCB	0.28	0.10					
		PS	0.22	0.13					
	3	CC	**0.36**	0.17	***	***			
		RCM	**0.20**	0.12	***		**		
		RCB	**0.27**	0.09			**	***	
		PS	**0.17**	0.08		***		***	
	4	CC	**0.35**	0.19	**	***			
		RCM	**0.20**	0.11	**		**		
		RCB	**0.25**	0.09			**	**	
		PS	**0.19**	0.09		***		**	

Bold numbers indicate significant (GLM repeated measures with the Huynh-Feldt ε-correction (α = 0.05)) differences among the criteria/alternatives.

(1) Bonferoni corrected significance levels of paired t-tests (* 0.10, ** 0.05, *** 0.01) between the indicated criteria/alternatives.

Table S 11: Architects' decision data in structural engineering

Decision			Alternative	Criteria		Criteria weights			Alternative weights per criteria					Alternative preference			
type	appl.	N		no.	criteria	mean	SD	sign. levels (1)	crit.	alternative	mean	SD	sign. levels (1)	alternative	mean	SD	sign. levels (1)
Project recommendation	External concrete								1	CC	**0.55**	0.42	** ***				
										RCB	**0.28**	0.31	** **				
										PS	**0.17**	0.19	*** **				
									2	CC	**0.40**	0.22	***				
										RCB	**0.24**	0.15	*** ***				
				1	Project specification	**0.13**	0.08	*** *** ***		PS	**0.36**	0.19	***				
			Conventional concrete (CC)	2	Expected costs	**0.21**	0.12	***	3	CC	**0.74**	0.36	*** ***	Conv. C.	**0.53**	0.21	*** ***
		48	Recycling concrete B (RCB)	3	Engineers' recommendation	**0.27**	0.12	*** ***		RCB	**0.10**	0.15	***	RC.C.	**0.21**	0.12	***
			Property specification (PS)	4	Image	**0.17**	0.07	*** ***		PS	**0.16**	0.26	***	open	**0.26**	0.15	***
				5	Aesthetical aspects	**0.22**	0.08	*** ***	4	CC	0.38	0.22					
										RCB	0.27	0.17					
										PS	0.34	0.16					
									5	CC	**0.52**	0.19	*** ***				
										RCB	**0.20**	0.10	*** **				
										PS	**0.28**	0.18	*** **				
	Internal concrete									CC	**0.55**	0.42	** ***				
										RCM	**0.28**	0.31	** **				
										PS	**0.17**	0.19	*** **				
									2	CC	**0.40**	0.21	***				
										RCM	**0.25**	0.15	*** *				
				1	Project specification	**0.15**	0.09	** *** *		PS	**0.35**	0.19	*				
			Conventional concrete (CC)	2	Expected costs	**0.21**	0.09	** *	3	CC	**0.71**	0.38	*** ***	CC	**0.52**	0.20	*** ***
		48	Recycling concrete M (RCM)	3	Engineers' recommendation	**0.28**	0.13	*** * *** **		RCM	**0.10**	0.15	*** *	RCM	**0.23**	0.12	***
			Property specification (PS)	4	Image	**0.16**	0.07	*** **		PS	**0.19**	0.30	*** *	PS	**0.26**	0.15	***
				5	Aesthetical aspects	**0.20**	0.08	* ** **	4	CC	0.37	0.19					
										RCM	0.32	0.18					
										PS	0.31	0.17					
									5	CC	**0.50**	0.19	*** ***				
										RCM	**0.22**	0.13	***				
										PS	**0.28**	0.16	***				
	Lean concrete								1	CC	**0.55**	0.42	** ***				
										RCM	**0.28**	0.31	** **				
										PS	**0.17**	0.19	*** **				
									2	CC	0.37	0.21					
										RCM	0.27	0.13					
				1	Project specification	**0.14**	0.08	*** ***		PS	0.36	0.18					
			Conventional concrete (CC)	2	Expected costs	**0.26**	0.12	*** *** ***	3	CC	**0.52**	0.42	***	CC	**0.46**	0.22	*** **
		48	Recycling concrete M (RCM)	3	Engineers' recommendation	**0.31**	0.11	*** *** ***		RCM	**0.14**	0.16	*** ***	RCM	**0.23**	0.11	*** ***
			Property specification (PS)	4	Image	**0.14**	0.07	*** ***		PS	**0.34**	0.36	***	PS	**0.31**	0.16	** ***
				5	Aesthetical aspects	**0.15**	0.07	*** ***	4	CC	0.37	0.20					
										RCM	0.30	0.16					
										PS	0.33	0.16					
									5	CC	**0.43**	0.19					
										RCM	**0.24**	0.13					
										PS	**0.33**	0.17					

Bold numbers indicate significant (GLM repeated measures with the Huynh-Feldt ε-correction (α = 0.05)) differences among the criteria/alternatives.
(1) Bonferoni corrected significance levels of paired t-tests (* 0.10, ** 0.05, *** 0.01) between the indicated criteria/alternatives.

Table S 12: Contractors' decision data in structural engineering

Decision			Alternative	Criteria		Criteria weights						Alternative weights per criteria							Alternative preference					
type	appl.	N		no.	criteria	mean	SD	sign. levels (1)				crit.	alternative	mean	SD	sign. levels (1)			alternative	mean	SD	sign. levels (1)		
	External concrete											1	CC	**0.87**	0.30	***	***							
													RCB	**0.10**	0.25	***								
													RCM	**0.03**	0.10		***							
												2	CC	**0.49**	0.22	***	***							
			Conventional concrete (CC)	1	Tender documents	**0.38**	0.18	***	***	***			RCB	**0.31**	0.16	***		**	CC	**0.69**	0.16	***	***	
		49	Recycling concrete B (RCB)	2	Economic aspects	**0.17**	0.11	***			*		RCM	**0.20**	0.18		***	**	RCB	**0.20**	0.11	***		***
			Recycling concrete M (RCM)	3	Experience	**0.24**	0.12		***		*	3	CC	**0.55**	0.17	***	***		RCM	**0.11**	0.09		***	***
				4	Technical aspects	**0.21**	0.12			***			RCB	**0.30**	0.12	***		***						
													RCM	**0.15**	0.13		***	***						
												5	CC	**0.60**	0.12	***	***							
													RCB	**0.28**	0.11	***		***						
													RCM	**0.11**	0.08		***	***						
Tender	Internal concrete											1	CC	**0.90**	0.26	***	***							
													RCB	**0.06**	0.18	***								
													RCM	**0.04**	0.11		***							
												2	CC	**0.50**	0.20	***	***							
			Conventional concrete (CC)	1	Tender documents	**0.36**	0.17	***	**	***			RCB	**0.32**	0.13	***		***	CC	**0.68**	0.15	***	***	
		49	Recycling concrete B (RCB)	2	Economic aspects	**0.19**	0.12	***					RCM	**0.18**	0.16		***	***	RCB	**0.21**	0.11	***		***
			Recycling concrete M (RCM)	3	Experience	**0.24**	0.11		**			3	CC	**0.57**	0.17	***	***		RCM	**0.11**	0.08		***	***
				4	Technical aspects	**0.21**	0.12			***			RCB	**0.29**	0.14	***		***						
													RCM	**0.14**	0.10		***	***						
												5	CC	**0.57**	0.13	***	***							
													RCB	**0.33**	0.14	***		***						
													RCM	**0.10**	0.08		***	***						
	Lean concrete											1	CC	**0.65**	0.45	***	***							
													RCB	**0.18**	0.35	***								
													RCM	**0.16**	0.33		***							
												2	CC	0.28	0.22									
			Conventional concrete (CC)	1	Tender documents	**0.27**	0.21						RCB	0.37	0.12				CC	**0.43**	0.25	***		
		49	Recycling concrete B (RCB)	2	Economic aspects	**0.28**	0.16	**					RCM	0.36	0.21				RCB	**0.32**	0.17		**	
			Recycling concrete M (RCM)	3	Experience	**0.26**	0.10		***			3	CC	**0.39**	0.21	**			RCM	**0.24**	0.16	***	**	
				4	Technical aspects	**0.19**	0.12	**	***				RCB	**0.36**	0.14		***							
													RCM	**0.25**	0.15	**	***							
												5	CC	**0.41**	0.22	***								
													RCB	**0.42**	0.18		***							
													RCM	**0.17**	0.13	***	***							

Bold numbers indicate significant (GLM repeated measures with the Huynh-Feldt ε-correction (α = 0.05)) differences among the criteria/alternatives.

(1) Bonferoni corrected significance levels of paired t-tests (* 0.10, ** 0.05, *** 0.01) between the indicated criteria/alternatives.

Table S 13: Public awarding authorities' decision data in civil engineering

Decision			Alternative	Criteria		Criteria weights						Alternative weights per criteria								Alternative preference						
type	appl.	N		no.	criteria	mean	SD	sign. levels [1]				crit.	alternative	mean	SD	sign. levels [1]				alternative	mean	SD	sign. levels [1]			
												1	SCS	**0.46**	0.16	***	***									
													RMCM	**0.32**	0.14	***		*								
													NSCS	**0.22**	0.19		***	*								
												2	SCS	**0.43**	0.18	***	***									
			Sustainable construction specification (SCS)	1	Social aspects	**0.16**	0.10	***	***				RMCM	**0.31**	0.14	***				SCS	**0.44**	0.14	***	***		
Project specification	general	50	Recycled mineral construction material (RMCM)	2	Economic aspects	**0.27**	0.13	***					NSCS	**0.26**	0.19		***			RMCM	**0.32**	0.13	***		*	
			No sustainable construction specification (NSCS)	3	Ecological aspects	**0.22**	0.14			***		3	SCS	**0.45**	0.15	**	***			NSCS	**0.24**	0.17		***	*	
				4	Technical aspects	**0.35**	0.16		***	***			RMCM	**0.36**	0.14	**		***								
													NSCS	**0.19**	0.15		***	***								
												4	SCS	**0.44**	0.18	***	***									
													RMCM	**0.32**	0.14	***										
													NSCS	**0.25**	0.19		***									
												1	CA	**0.42**	0.36	**	***									
													RAP	**0.24**	0.25											
													RAA	**0.20**	0.20	**										
													PS	**0.16**	0.12		***									
												2	CA	**0.25**	0.15											
													RAP	**0.23**	0.13											
Project confirmation / Tender documents	Bound sub-base	50	Conventional aggregate (CA)	1	Project recommendation	**0.32**	0.16	**	***				RAA	**0.22**	0.09	**				CA	**0.30**	0.18	*			
			Recycled aggregate P (RAP)	2	Expected costs	**0.30**	0.15			***			PS	**0.31**	0.16	**				RAP	**0.25**	0.14				
			Recycled aggregate A (RAA)	3	Political aspects	**0.22**	0.13	**			**	3	CA	0.23	0.13					RAA	**0.22**	0.09	*			
			Property specification (PS)	4	Image	**0.16**	0.09		***	***	**		RAP	0.28	0.13					PS	**0.23**	0.09				
													RAA	0.25	0.09											
													PS	0.24	0.14											
												4	CA	0.28	0.14											
													RAP	0.25	0.11											
													RAA	0.24	0.09											
													PS	0.23	0.11											
												1	CA	**0.48**	0.42	***	***									
													RAB	**0.32**	0.38			***	***							
													RAM	**0.10**	0.12	***		***								
													PS	**0.10**	0.12		***		***							
												2	CA	0.24	0.14											
													RAB	0.25	0.11											
	Unbound sub-base	50	Conventional aggregate (CA)	1	Project recommendation	**0.32**	0.15	*	***				RAM	0.23	0.12					CA	**0.33**	0.19	***	***		
			Recycled aggregate B (RAB)	2	Expected costs	**0.29**	0.14			***			PS	0.28	0.13					RAB	**0.28**	0.17			***	*
			Recycled mixed rubble aggregate (RAM)	3	Political aspects	**0.23**	0.14	*			*	3	CA	0.24	0.13					RAM	**0.18**	0.08	***		***	
			Property specification (PS)	4	Image	**0.16**	0.10		***	***	*		RAB	0.29	0.13					PS	**0.21**	0.10		***		*
													RAM	0.22	0.11											
													PS	0.25	0.12											
												4	CA	**0.30**	0.17	*	**									
													RAB	**0.28**	0.10			***	**							
													RAM	**0.21**	0.10	*		***								
													PS	**0.21**	0.10		**		**							
												1	CC	**0.42**	0.36	***	***									
													RCM	**0.16**	0.12	***		***								
													RCB	**0.26**	0.27				***							
													PS	**0.16**	0.12		***	***	***							
												2	CC	0.25	0.15											
													RCM	0.24	0.10											
	Lean concrete	50	Conventional concrete (CC)	1	Project recommendation	**0.31**	0.13	**	***				RCB	0.24	0.09					CC	**0.31**	0.18	*	*		
			Recycling concrete M (RCM)	2	Expected costs	**0.28**	0.14			**			PS	0.28	0.13					RCM	**0.21**	0.08	*			
			Recycling concrete B (RCB)	3	Political aspects	**0.22**	0.12	**				3	CC	0.25	0.14					RCB	**0.26**	0.13				
			Property specification (PS)	4	Image	**0.19**	0.09		***	**			RCM	0.24	0.09					PS	**0.22**	0.08		*		
													RCB	0.26	0.10											
													PS	0.25	0.11											
												4	CC	0.27	0.15											
													RCM	0.25	0.11											
													RCB	0.27	0.09											
													PS	0.21	0.09											

Bold numbers indicate significant (GLM repeated measures with the Huynh-Feldt ε-correction (α = 0.05)) differences among the criteria/alternatives.
[1] Bonferoni corrected significance levels of paired t-tests (* 0.10, ** 0.05, *** 0.01) between the indicated criteria/alternatives.

Table S 14: Engineers’ decision data in civil engineering

Decision			Alternative	Criteria		Criteria weights					Alternative weights per criteria									Alternative preference						
type	appl.	N		no.	criteria	mean	SD	sign. levels [1]			crit.	alternative	mean	SD	sign. levels [1]					alternative	mean	SD	sign. levels [1]			
Project recommendation											1	CA	0.25	0.20												
												RAP	0.28	0.13												
												RAA	0.22	0.12												
												PS	0.25	0.15												
											2	CA	0.19	0.18												
												RAP	0.29	0.13												
	Bound sub-base	39	Conventional aggregate (CA)	1	Project specification	**0.13**	0.12	***	***	***		RAA	0.26	0.11						CA	**0.32**	0.16	***			
			Recycled aggregate P (RAP)	2	Expected costs	**0.26**	0.15	***				PS	0.27	0.15						RAP	**0.26**	0.11		**		
			Recycled aggregate A (RAA)	3	Experience	**0.27**	0.11		***		3	CA	**0.37**	0.17	*	***	***			RAA	**0.19**	0.09	***	**		
			Property specification (PS)	4	Law and standards	**0.34**	0.16			***		RAP	**0.26**	0.13	*			***		PS	**0.24**	0.10				
												RAA	**0.16**	0.10		***		***								
												PS	**0.22**	0.13			***									
											4	CA	**0.39**	0.19	***	***	***									
												RAP	**0.23**	0.11	***											
												RAA	**0.17**	0.09		***										
												PS	**0.21**	0.10			***									
											1	CA	**0.28**	0.19												
												RAB	**0.30**	0.12	***	**										
												RAM	**0.21**	0.11	***											
												PS	**0.21**	0.12		**										
											2	CA	0.23	0.20												
												RAB	0.25	0.11												
	Unbound sub-base	39	Conventional aggregate (CA)	1	Project specification	**0.13**	0.13	***	***	***		RAM	0.26	0.11						CA	**0.35**	0.17	*	***	***	
			Recycled aggregate B (RAB)	2	Expected costs	**0.26**	0.14	***				PS	0.26	0.14						RAB	**0.25**	0.10	*			***
			Recycled mixed rubble aggregate (RAM)	3	Experience	**0.27**	0.11		***		3	CA	**0.39**	0.18	***	***	***			RAM	**0.19**	0.07		***		***
			Property specification (PS)	4	Law and standards	**0.33**	0.16			***		RAB	**0.24**	0.11	***			**		PS	**0.21**	0.10			***	
												RAM	**0.17**	0.09		***		**								
												PS	**0.21**	0.12			***									
											4	CA	**0.40**	0.18	***	***	***									
												RAB	**0.24**	0.10	***			***	*							
												RAM	**0.17**	0.08		***		***								
												PS	**0.19**	0.09			***		*							
											1	CC	**0.26**	0.20												
												RCM	**0.25**	0.12	*											
												RCB	**0.31**	0.11	*	***										
												PS	**0.18**	0.11		***										
											2	CC	0.21	0.18												
												RCM	0.29	0.12												
	Lean concrete	39	Conventional concrete (CC)	1	Project specification	**0.15**	0.14	**	***	***		RCB	0.28	0.10						CC	**0.31**	0.17	**			
			Recycling concrete M (RCM)	2	Expected costs	**0.26**	0.14	**				PS	0.22	0.13						RCM	**0.23**	0.10		*		
			Recycling concrete B (RCB)	3	Experience	**0.28**	0.13		***		3	CC	**0.36**	0.17	***	***				RCB	**0.27**	0.08		*	***	
			Property specification (PS)	4	Law and standards	**0.31**	0.17			***		RCM	**0.20**	0.12	***		**			PS	**0.19**	0.09	**		***	
												RCB	**0.27**	0.09			**	***								
												PS	**0.17**	0.08		***		***								
											4	CC	**0.35**	0.19	**	***										
												RCM	**0.20**	0.11	**		**									
												RCB	**0.25**	0.09			**	**								
												PS	**0.19**	0.09		***		**								

Bolt numbers indicate significant (GLM repeated measures with the Huynh-Feldt ε-correction (α = 0.05)) differences among the criteria/alternatives.

[1] Bonferoni corrected significance levels of paired t-tests (* 0.10, ** 0.05, *** 0.01) between the indicated criteria/alternatives.

Table S 15: Contractors' decision data in civil engineering

Decision			Alternative	Criteria		Criteria weights			Alternative weights per criteria							Alternative preference				
type	appl.	N		no.	criteria	mean	SD	sign. levels (1)	crit.	alternative	mean	SD	sign. levels (1)			alternative	mean	SD	sign. levels (1)	
Tender	Bound sub-base								1	CA	0.41	0.23								
										RAP	0.32	0.13								
										RAA	0.27	0.19								
									2	CA	0.32	0.25								
										RAP	0.32	0.10								
				1	Selection criteria	0.27	0.15			RAA	0.37	0.22								
			Conventional aggregate (CA)	2	Economic aspects	0.22	0.12		3	CA	**0.45**	0.21	*	**		CA	**0.42**	0.19	*	
		23	Recycled aggregate P (RAP)	3	Experience	0.20	0.09			RAP	**0.30**	0.11	*			RAP	**0.30**	0.13		
			Recycled aggregate A (RAA)	4	Technical aspects	0.16	0.09			RAA	**0.25**	0.18		**		RAA	**0.27**	0.15	*	
				5	Tender documents	0.16	0.08		4	CA	**0.43**	0.22	*							
										RAP	**0.31**	0.13								
										RAA	**0.25**	0.16	*							
									5	CA	0.51	0.42								
										RAP	0.25	0.34								
										RAA	0.25	0.34								
	Unbound sub-base								1	CA	**0.48**	0.19	*	***						
										RAB	**0.34**	0.12	*		***					
										RAM	**0.18**	0.14		***	***					
									2	CA	0.35	0.25								
										RAB	0.33	0.13								
				1	Selection criteria	0.26	0.16			RAM	0.31	0.22								
			Conventional aggregate (CA)	2	Economic aspects	0.19	0.13		3	CA	**0.45**	0.19	***			CA	**0.46**	0.19	***	
		23	Recycled aggregate B (RAB)	3	Experience	0.20	0.09			RAB	**0.36**	0.16		***		RAB	**0.35**	0.15		***
			Recycled mixed rubble aggregate (RAM)	4	Technical aspects	0.18	0.12			RAM	**0.19**	0.15	***	***		RAM	**0.18**	0.12	***	***
				5	Tender documents	0.17	0.08		4	CA	**0.47**	0.20	*	***						
										RAB	**0.32**	0.14	*		*					
										RAM	**0.21**	0.16		***	*					
									5	CA	**0.58**	0.46	***							
										RAB	**0.36**	0.45		**						
										RAM	**0.06**	0.13	***	**						
	Lean concrete								1	CC	**0.47**	0.22	**	**						
										RCM	**0.28**	0.15	**							
										RCB	**0.25**	0.14		**						
									2	CC	0.35	0.27								
										RCM	0.30	0.20								
				1	Selection criteria	0.26	0.16			RCB	0.34	0.14								
			Conventional concrete (CC)	2	Economic aspects	0.19	0.09		3	CC	0.43	0.24				CC	**0.44**	0.22	**	
		23	Recycling concrete M (RCM)	3	Experience	0.20	0.09			RCM	0.28	0.17				RCM	**0.31**	0.19		
			Recycling concrete B (RCB)	4	Technical aspects	0.19	0.11			RCB	0.28	0.13				RCB	**0.25**	0.09	**	
				5	Tender documents	0.16	0.08		4	CC	**0.42**	0.22	*							
										RCM	**0.30**	0.17								
										RCB	**0.27**	0.10	*							
									5	CC	**0.58**	0.46	***							
										RCM	**0.36**	0.45		**						
										RCB	**0.06**	0.13	***	**						

Bold numbers indicate significant (GLM repeated measures with the Huynh-Feldt ε-correction (α = 0.05)) differences among the criteria/alternatives.
(1) Bonferoni corrected significance levels of paired t-tests (* 0.10, ** 0.05, *** 0.01) between the indicated criteria/alternatives.

Supporting information to publication III

Supporting information to the manuscript entitled;

Enhancing recycling of construction materials: the role of empirically based decision parameters

Christof Knoeri [1,3], Igor Nikolic [2], Hans-Joerg Althaus [3], Claudia R. Binder [4]

[1] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT UK
[2] Section Energy & Industry, Faculty of Technology, Policy and Management, Delft University of Technology, The Netherlands
[3] Laboratory for Technology and Society, Empa, Swiss Federal Laboratories for Materials Science and Technology, Duebendorf, Switzerland
[4] Human Environment Relations, Department of Geography, University of Munich, Germany

Table of content

List of figures

List of tables

1. Part I: Complete model description with the ODD protocol

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing agent-based models (Grimm et al. 2006; Grimm et al. 2010). Below we repeat the first two ODD protocol section from the manuscript in order to provide a complete and independent model description as recommended in Grimm et al. (2010).

1.1. Overview

1.1.1. Purpose of the model

This model aims at representing the decision-making and behaviour of interacting construction stakeholders when deciding what kind of construction material to apply. It was designed to analyse key factors affecting the demand for conventional materials (i.e. conventional concrete with natural gravel and sand aggregates) or recycled materials (i.e. recycled concrete where natural aggregates are substituted to a certain extent with recycled aggregates), and to develop scenarios leading to a maximal reuse. The main output variable considered is therefore the fraction of recycled concrete applied. The main driver of the model is construction investments broken down into projects to be executed by construction stakeholders.

1.1.2. Entities, state variables and scales

Entities and state variables: The following entities are included in the model: agents representing construction stakeholders (i.e. awarding authorities, engineers, architects and contractors), projects, grid cells (i.e. virtual geographical location) and the global environment representing the construction market (i.e. construction investments and materials available).

Awarding authorities represent private persons, companies, or public authorities awarding prime building contracts, for different purposes (e.g. personal use, economic reasons, public building requirements). *Engineers* represent the actors responsible for the static design of the concrete structure in buildings; *architects* the stakeholders designing and supervising the construction, and c*ontractors* the companies providing the concrete work. All agents are located at a unique location and hold an identity number, construction related variables, such as construction capacity, building radius and experience, and multi-criteria decision variables for each distinct decision. In total, 5788 agents are implemented, representing the statistical distribution of construction stakeholders in the case study. *Projects* represent the individual construction projects on which these agents interact. Besides the basic project variables such as construction year, sum, investor type and material amount and type applied, the projects track the agents involved and the outcome of all agents' decisions. Per year about 450 projects are executed. *Grid cells* represent virtual construction sites of 30x30m (Table 1). The *observer or global environment* (i.e. construction market) is the only entity on the system level, defining the annual construction investments and the potential recycling aggregates supply. In addition it holds the variables for demand and supply accounting and agent specific parameters for scenario measures (Table 2).

Model, spatial and temporal scales: The model was designed to represent individual construction projects with a model to reality relation of 1:100 (in terms of agents and projects). This means that 100 times less agents are represented in the model and each construction project is 100 times larger, respectively. The model has no explicit spatial relation, however; agents are distributed randomly across a virtual space for local interaction. The virtual space is an unwrapped square (to see edge effects) of 300 x 300 grid cells theoretically representing an area of 3x3km. Agents' building radii were derived from Knoeri et al. (2011b) and were adjusted to the model scale (e.g. mean building radius of 30 units (0.3km) for commercial and private awarding authorities and 50 units (0.5km) for public awarding authorities). One time step represents one year and simulations were run for 40 years (2010-2050) for material flow analysis and for 10 years (2010-2020) for the demand sensitivity analysis.

Table 1: Entities, state variables and attributes

entity	type (number)	state variables and attributes
Agents	***Awarding authority (AA)*** (5700 private, 83 commercial and 5 public AA)	• *Awarding authority type:* private, commercial or public AA • *Construction capacity:* maximum executable projects per year and AA • *Building radius:* radius within projects are build [grid cell units] • *Agent selection weights:* weights of the reference and personal contact criteria for stakeholder interaction • *Specification option availability:* Frequency of project specification decisions where sustainable construction is an option (awareness) • *Multi-criteria project-specification decision variables* • *Multi-criteria project-confirmation decision variables* • *Multi-criteria tender-selection decision variables* • *Location: Grid cell (patch occupied by only this agent)* • *Identity number*
	Engineers (46)	• *Projects together:* percentage of project with the selecting AA in the last "agent experience time" years • *Specification sensitivity:* probability of considering RMCM as an option if AA specified sustainable construction • *Multi-criteria design-specification decision variables* • *Location: Grid cell (patch occupied by only this agent)* • *Identity number*
	Architects (18)	• *RMCM experience:* percentage of RC applied in the last "agent experience time" years • *Projects together:* percentage of project with the selecting AA in the last "agent experience time" years • *Specification sensitivity:* probability of considering RMCM as an option if AA specified sustainable construction or engineer specified RMCM • *Multi-criteria project-recommendation decision variables* • *Location: Grid cell (patch occupied by only this agent)* • *Identity number*
	Contractors (25)	• *RMCM experience:* percentage of RC applied in the last "agent experience time" years • *Multi-criteria tender-submission decision variables:* • *Tender variables: material and price of the tender* • *Tender utility: Utility of AA for contractors tender* • *Location: Grid cell (patch occupied by only this agent)* • *Identity number*
Projects	(~450 / year)	• *Investor type:* private, commercial or public • *Construction year:* • *Construction sum:* [Mio CHF] (with model relation of 1:100 each project is 100 times larger) • *Material amount:* amount of concrete used in the project in [t] • *Construction stakeholder variables:* AA, engineer, architect and contractor involved in the project • *Decision outcome of all decision:* 0 for conventional concrete (CC) and 1 for RC • *Materials applied:* 0 if CC, 1 if RC • *Location: Grid cell (patch occupied by only this project)* • *Identity number*
Grid cells	(90000)	• *X and Y coordinate indicating the position on the 300x300 grid landscape*

Table 2: State variables and parameters of the global environment entity representing the construction market

Construction market state variables and parameters

Construction investment parameters:

- *Construction scenario:* used for construction investment and RC aggregate supply calculation (-1 = minimal, 0 = trend, 1 = maximal)
- *Annual construction investment:* Overall building construction investment calculated with power-low trend extrapolation function
- *Construction fractions:* Fraction of private, commercial or public investment
- *Mean investment sums:* Mean private, commercial or public project sums
- *Mean construction capacity:* Mean annual private, commercial or public investment sums per AA
- *Mean construction mass per investment:* concrete mass [t] per Mio CHF invested (Mean 252 StD 107)
- *Private investment* = annual construction investment * private investment fraction
- *Commercial investment* = annual construction investment * commercial investment fraction
- *Public investment =* annual construction investment * public investment fraction

Recycling aggregates supply parameters:

- *Annual construction and demolition (C&D) waste volume:* Overall C&D waste volume calculated with power-low trend extrapolation function
- *Concrete waste fraction:* concrete waste fraction in % by volume (0.1524)
- *Concrete waste density:* 2.4 t/m^3 concrete waste
- *Residual mineral waste fraction:* roads, masonry and mineral waste fraction in % by volume (0.444)
- *Residual waste density:* 1.632 t/m^3 residual waste
- *Recycling efficiency: efficiency of the recycling process, fraction of C&D waste usable as aggregates 95%*
- *Annual concrete rubble supply* = annual construction waste volume * concrete waste fraction * concrete waste density * recycling efficiency
- *Annual mixed rubble supply* = annual construction waste volume * residual mineral waste fraction * residual waste density * recycling efficiency

Material demand variables:

- *Amount of current rmcm applied:* material amount of all projects with RC in the current year [t]
- *Amount of current cm applied:* material amount of all projects with CC in the current year [t]
- *Current fraction rmcm applied* = Amount of current rmcm applied / material amount of all projects current year [t]
- *Total rmcm applied*: all time amount of RC applied [t]
- *Total cm applied*: all time amount CC applied [t]
- *Global fraction rmcm applied*: average fraction over the simulation years
- *Concrete rubble demand* = amount of current rmcm applied * (1 - RC_M fraction) * recycling aggregates substitution fraction [t]
- *Mixed rubble demand* = amount of current rmcm applied * RC_M fraction * recycling aggregates substitution fraction [t]
- RMCM image: Global image variable set to the current fraction of RC applied, used to update agents experience variables

Material demand parameters:

- *RC-M fraction:* fraction of recycled concrete which is RC-M (all lean concrete + a fraction of the rest => default 10%)
- Recycling aggregates substitution fraction: fraction of recycled aggregates substituted, two scenarios min 25% and ref. 40% (Knoeri et al. submitted)

Agent specific parameters:

- *Agents experience time:* number of years agents remember their construction partners and materials they used [0-10 years, default 5 years]
- *AA specification availability:* mean (private, commercial or public) AA`s frequency of project specification decisions where sustainable construction is an option (awareness)
- *Engineers project specification sensitivity:* engineers` probability to consider RC as an options if sustainable construction was specified by the AA (0-1, default: mean 0.5, StD 0.2)
- *Architects specification sensitivity:* architects` probability to consider RC as an options if sustainable construction was specified by the AA, or RC by the engineer (0-1, default: mean 0.5, StD 0.2)
- *Contractors tender probability:* percentage of RC considered by contractors in their tender decision when no CC is specified in the tender documents (default 0.1)

1.1.3. Process overview and scheduling

To set up the model all investment and material flow parameters as well as the initial number of agents are initialized. The main procedure, being executed every time step (i.e. year) by the observer, consists of the following five steps. First, the annual construction investments are calculated and accordingly this year's projects created. Second, the potential supply of recycled aggregates is calculated. Third, the projects are distributed to enough awarding authorities and randomly executed (i.e. if the number of projects exceeds the construction capacity of the awarding authorities new ones are created). Fourth, the global demand values and agent properties are updated according to the projects finished. Fifth and finally, the projects older than the limits of the agent's memory are erased from the model (Figure 1).

```
for each year (< simulation end year)
    calculate annual investments and create this year's projects
    calculate annual potential supply of recycled aggregates
    distribute projects to AA and execute projects randomly
    update global demand values and agent properties
    delete projects older than agents-experience-time
end
```

Figure 1: Pseudo-code of the main procedure

```
Awarding authority
to execute project
  if sustainable construction is an option
      [make project specification SCS or CC]
  select engineer according to location, contact and references
      [ask him to make his design specification]
  select architect according to location, contact and references
      [ask him to make his project recommendation]
  if sustainable constr. is specified, eng. or arch. recommend RC
      [make project confirmation]
  select potential contractors according to location
      [ask them to make an offer]
  if RC is tendered at all [make multi-criteria selection]
  else [select the tender with the lowest price]
  deduct the material chosen from the market
      [RC applied if available, otherwise CC]
  set materials applied in the project
end
```

```
Engineer
to make design specification
  if (SCS + pursued) or (own idea)
      [make multi-criteria design specification]
  else [specify CC]
end
```

```
Architect
to make project confirmation
  if (SCS or eng. recom. + pursued) or (own idea)
      [make multi-criteria project recommendation]
  else [recomend CC]
end
```

```
Contractor
to make an offer
  if (RC in tender docs or own idea + RC are available)
      [make multi-criteria tender decision]
  else [tender CC and price]
end
```

Figure 2: Pseudo-code of awarding authorities project execution subroutine calling of engineer's, architect's and contractor's subroutines.

The most important sub model is the "execute project" procedure presented in Figure 2 which itself contains several subroutines (A complete specification of the subroutines is presented in SI Table 5). This project execution of the awarding authorities basically reflects the agent interaction chain derived from the agent-operationalization approach (Knoeri et al. 2011a;

Knoeri, et al. 2011b). Once a project is assigned to an awarding authority, if sustainable construction is an option at all, this agent first makes his project specification, followed by selecting an engineer to get a design specification and an architect for a project recommendation. These selections both are based on neighbourhood, personal contacts and references. Engineer and architect interact through the project as the architect considers the engineer's design specification as a criterion, which is stored in the project. Having the recommendation from the experts, the awarding authority makes the project confirmation decision and selects the three closest contractors for tendering. Including tender price and expert recommendation the awarding authority awards the contract to the contractor with the highest utility. If the proposed recycled aggregates are out of stock the agents switch back to conventional materials. Finally the demanded materials are deducted from the market and assigned to the project. The availability of the recycling option for the construction experts (i.e. engineers, architects and contractors) depends on other agents' specifications or recommendation and own preferences. For example, engineers consider recycled concrete only as an option, either if the awarding authority specified sustainable construction and the engineer pursues by relating that to recycled concrete, or he comes up with the recycling option by himself. In all other cases he recommends conventional concrete. The empirical data for the application specific decisions (e.g. from design specification to tender selection) were aggregated from decisions regarding structural indoor and outdoor concrete application since they have been found to correspond to a large extent (Knoeri, et al. 2011b). Lean concrete application decisions were neglected due to their little contribution (< 4%) to the overall concrete flows (Figure 5).

Implementation: The model is implemented in Netlogo 5.0 (Wilensky 1999) and source code is provided at the openabm.org model archive (http://openabm.org/model/3294/version/1/view).

1.2. Design concepts

In the following we present the main design concepts applied to the model. Concepts considered being not important for the question addressed are therefore not applied and omitted here. Please see Railsback (2001) and Grimm et al. (2010) for further readings on design concepts.

Basic principles: Although the main driver of the model was the external construction investment, regarding the main purpose (i.e. modelling of the demand for different type of materials) the model relied solely on the agent interaction. This allowed us analysing the drivers behind the material demand independent of the obviously complex dynamics of the building sector. For the agent operationalization the agent-operationalization approach was applied (Knoeri, et al. 2011a). Further, for the individual decision-making process the model assumes rational actors in a sense as they chose the best performing option from the multi-criteria decision using the analytical hierarchy process (AHP) developed by Saaty (1980, 1990). This assumption is empirically supported by the good consistencies of decision output and behaviour in construction stakeholders` decisions (Knoeri, et al. 2011b).

Emergence: The model was designed to explore the processes that give rise to the demand of recycled concrete. The key output therefore is the fraction of recycled materials applied emerging from the agent interaction. Since the total amount of materials applied was directly linked to the construction investments its outcome was rather predictable. However, linking demand and potential supply of recycled construction materials led to useful insights on a system level. *Adaptation:* The agents adapt in two different ways to their environment. (i) Their multi-criteria decisions include criteria from other agents and the environment (e.g. recommendations, law and standards). (ii) The agent selection includes adaptation to previous interactions (i.e. personal contact) as well as their references. *Objectives:* The agents use optimization traits (e.g. choose the option with the highest utility) in their multi-criteria decisions. *Learning:* As agents adapt their economic, image and experience parameters to the respective system values and their personal experience, they learn, although in a simple way, from their and the system`s past. *Prediction:* Agents do not use explicitly prediction, although the expected utility in the multi-criteria decision could be seen as a simple form of prediction. Sensing: Agents know all their internal variables (e.g. decision-criteria) and are able to sense variables of other agents (e.g. experience and references) for the project interaction. However, they have limited information of the construction market, as some might know the price and amount of available materials while others do not know that certain materials are an alternative option. *Interaction:* The agents interact in various ways with each other: (i) Direct interaction on the construction project with other agents directly affecting their behaviour (e.g. selection, recommendation) (Knoeri, et al. 2011a). The required communication information is stored in the projects. (ii) Indirect interaction through resource consumption (i.e. recycled aggregates), competition (i.e. tender selection), and systemic variables such as the image of recycled materials. *Stochasticity:* Although the model was based on extensive empirical work (Knoeri, et al. 2011b), stochasticity was either used to represent the empirical distributions (e.g. set decision parameters), control the scheduling (e.g. random project execution) or induce variability for less important assets (e.g. small price variability). Observation: The main data collected from the model were the global fraction of RC applied and the demand for different types of materials on the system level in terms of m^3 and t. In addition, the number of RC decision outcomes of agents` multi-criteria decisions was observed. Further the experience of construction experts (i.e. architects, engineers and contractors) has been tracked.

1.3. Details

1.3.1. Initialization

Figure 3 show the model setup procedure called at the start of each simulation run. Initially simulation time is set to the simulation start year parameter (2010 for most of the simulation experiments. Next, the share of the different AA groups on the total construction investment is set (i.e. 32.2% private, 49.5% commercial, and 18.2% public investments), their mean projects investment is divined (i.e. 0.840 for private, 1.155 for commercial, and 0.969 Mio CHF for public

AA (Figure 4)), and their mean construction capacities are initialized (i.e. 0.03 for private, 3 for commercial, and 10 construction projects per year for public AA). The data were taken from Knoeri et al. (2011b). Subsequently, the mean concrete mass [t] per Mio invested CHF (Mean 252, StD 107) is set. We used the average value across construction categories (Figure 5) since the most deviant categories (i.e. industrial and other buildings) accounted only for a minor share of the investments (Figure 6). Then the current fraction of RMCM applied and the RMCM image are set according to the initial fraction of RMCM applied. Before calling the agent setup subroutines the initial numbers of agents are specified (5700 private AA, 83 commercial AA, 5 public AA, 46 architects, 18 engineers, and 25 contractors). Finally the agent setup subroutines for each agent category are called creating the initial agent set for each group. They basically set each agent at a random free position, and draws all its decision criteria values from stochastic distributions derived from Knoeri et al. (2011b) or the parameters specified in the interface. A detailed description of each agent group setup procedure is provided in Table 5.

```
to setup
  set simulation time to the start year
  set AAs` investment fractions, mean project investments and construction capacities
  set mean concrete mass per investment
  set the initial RMCM fraction and RMCM image
  define agent numbers for agent initialization
  setup awarding authorities
  setup architects
  setup engineers
  setup contractors
end
```

Figure 3: Main model initialization procedure

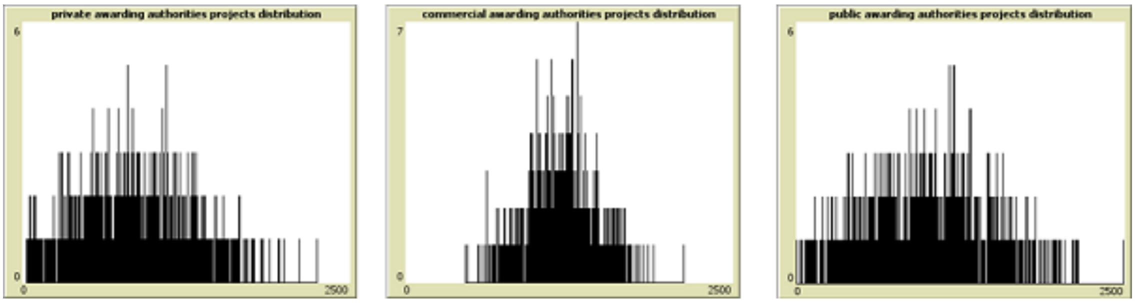

Figure 4: Example project size [1000 CHF] **distributions of private, commercial and public awarding authorities**

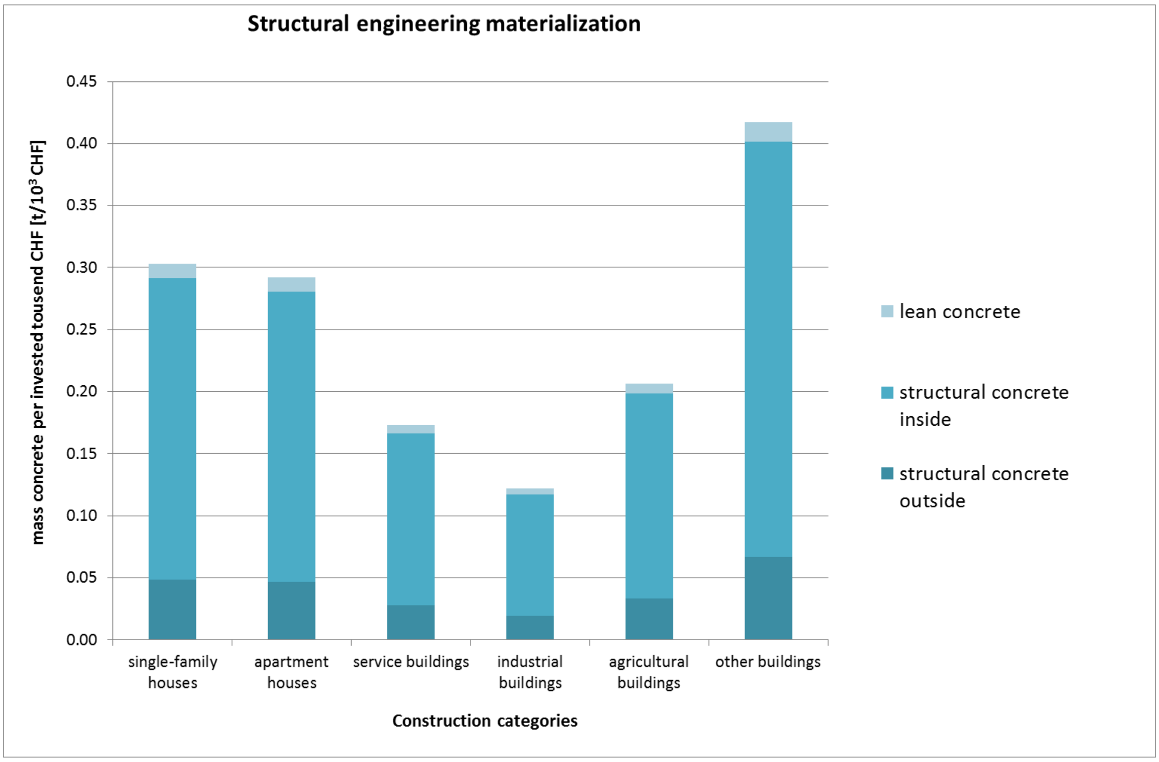

Figure 5: Structural engineering materialization of different construction categories (Own Figure, data from FOEN (2008) and BfS (2008), rendered plausible with Lichtensteiger (2006) and Mauch & Scheidegger (1996))

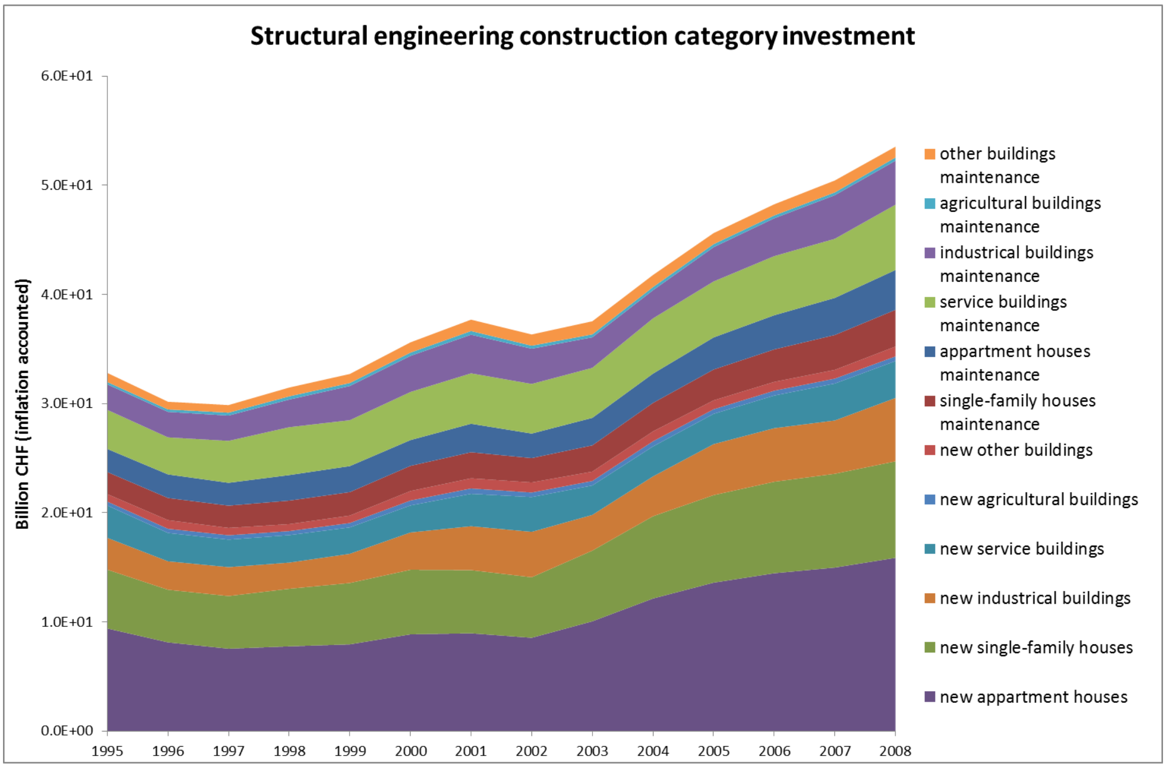

Figure 6: structural engineering investment in different categories over time (Own graph, data from BfS (2008))

Besides simulation start and end time, and switches for different model versions (e.g. investment scenarios, price and usage sensitivity) a range of global (Table 3) and agent specific parameters (Table 4) are defined in the Netlogo interface which are used in the setup procedures to initialize the model. They are the leavers to interfere with the model used in different simulation experiments. For a better handling of experimental runs they are also captured in the reference experiment procedure, which resets all the parameters to their default values and does a new model setup. Many of them are already listed in the state variable lists in section 1.1.2. However for a better understanding of possible leavers and scenarios we provide separate comprehensive tables of the interface parameters (Table 3 + Table 4).

Table 3: Global scenario parameters

Global parameters	Default value	Description and source
initial-RMCM-application	0.08	8 % of the structural concrete decisions (Knoeri, et al. 2011b)
RA-substitution-fraction	0.25	fraction of recycled aggregates substituted, two scenarios min 25% and ref. 40% (Knoeri et al. 2012)
RC-M-fraction	0.1	fraction of recycled concrete which is RC-M (all lean concrete + a 10 % fraction of the rest => assumption)
recycling-efficiency	0.95	efficiency of the recycling process, fraction of C&D waste usable as aggregates ca. 95% after treatment (Knoeri, et al. 2012)
Percental-RCtoCC-price-difference	0	By default set to equal prices although 5% lower for recycled concrete (Knoeri, et al. 2011b)
agents-experience-time	5	Number of years agent remember their actions

Table 4: Agents mean decision scenario parameters captured in the interface

Agents mean decision parameters	Default value	Description and source
private-AA-specification-availability	0.57	Percentage where in AAs` project specification sustainable construction or RMCM is an available option (Source: Knoeri et al. (2011b))
commercial-AA-specification-availability	0.42	
public-AA-specification-availability	0.40	
SustainableConstructionSpecification-SocialAspects	0.75	Mean AAs` project specification criteria values (Source: Knoeri et al. (2011b))
SustainableConstructionSpecification-EconomicAspects	0.75	
SustainableConstructionSpecification-EcologicalAspects	0.75	
PrivateProjectConfirmation-RMCMExpectedPrices	0.45	Mean private AAs` project confirmation criteria values (Source: Knoeri et al. (2011b))
PrivateProjectConfirmation-RMCMTechnicalAspects	0.45	
PrivateProjectConfirmation-RMCMEcologicalAspects	0.55	
CommercialProjectConfirmation-RMCMEconomicAspects	0.45	Mean commercial AAs` project confirmation criteria values (Source: Knoeri et al. (2011b))
CommercialProjectConfirmation-RMCMTechnicalAspects	0.50	
CommercialProjectConfirmation-RMCMEcologicalAspect	0.50	
PublicProjectConfirmation-RMCMExpectedPrices	0.40	Mean public AAs` project confirmation criteria values (Source: Knoeri et al. (2011b))
PublicProjectConfirmation-RMCMPolicy	0.55	
PublicProjectConfirmation-RMCMImage	0.50	
PrivatTenderSelection-RMCMEcologicalAspects	0.60	Mean private AAs` tender selection ecological aspects value (Source: Knoeri et al. (2011b))
CommercialTenderSelection-RMCMMarketability	0.40	Mean commercial AAs` tender selection marketability value (Source: Knoeri et al. (2011b))
Engineers-project-spec-sensitivity	0.5	Engineers` probability to consider RMCM as an option when the AA specified sustainable construction (assumption)
engineers-design-specification-probability	0.1	Engineers` probability to consider RMCM on their own (assumption: about the amount of initial rmcm project decisions)
DesignSpecification-RMCMExpectedPrices	0.4	Mean engineers` design specification criteria values (Source: Knoeri et al. (2011b))
DesignSpecification-RMCMExperience	0.4	
DesignSpecification-RMCMNorm	0.45	
Architects-spec-sensitivity	0.5	Architects` probability to consider RMCM as an option when the AA specified sustainable construction or the engineer proposed RMCM (assumption)
architects-recommendation-probability	0.1	Architects` probability to consider RMCM on their own (assumption: about the amount of initial rmcm project decisions)
ProjectRecommendation-RMCMExpectedPrices	0.4	Mean architects` project recommendation criteria values (Source: Knoeri et al. (2011b))
ProjectRecommendation-RMCMImage	0.45	
ProjectRecommendation-RMCMAesthetics	0.35	
contractors-tender-probability	0.1	Contractors` probability to consider RMCM on their own (assumption: about the amount of initial rmcm project decisions)
TenderSubmission-RMCMEconomicAspects	0.5	Mean contractors` tender submission criteria values (Source: Knoeri et al. (2011b))
TenderSubmission-RMCMExperience	0.45	
TenderSubmission-RMCMTechnicalAspects	0.4	

1.3.2. Input data

Besides the above described agents` decision making data used for the model initialization, the model uses external data to represent two processes that change over time; (i) construction investments driving the number of projects to be executed, and (ii) construction waste volumes limiting the potential available amount of recycled aggregates. Both time series were derived from power law trend extrapolations of available historical data (e.g. 1995-2008) until 2050. This ignores or levels out cyclic patterns observed in construction investments (Davis & Heathcote 2005; Suarezvilla & Hasnath 1993). However, since the model was not aiming at representing construction investments the simplification was accurate. Historical data for construction investments are taken from the Swiss Federal Bureau of Statistics (BfS) annually taken building and construction statistics (BfS 2008). Data availability for construction waste volumes is rather poor; therefore we draw upon updated model calculations from Wuest & Partner AG published as Swiss Federal Office for the Environment reports (FOEN 2001a, 2001b, 2008). In addition to the trend extrapolation scenario a maximal and minimal construction investment/waste scenario were simulated after 2008. This presumes that demolition of buildings increases with increasing investments, which is reasonable since highest construction investments are made in the suburban and urban regions (BfS 2008) where old buildings have to make room. Formulas and parameters of the scenario functions are provided in Table 5 in the description of the calculate-investments-and-create-projects and calculate-RC-supply procedures. The scenario functions are displayed in Figure 7 and Figure 8 in relation to the historical data.

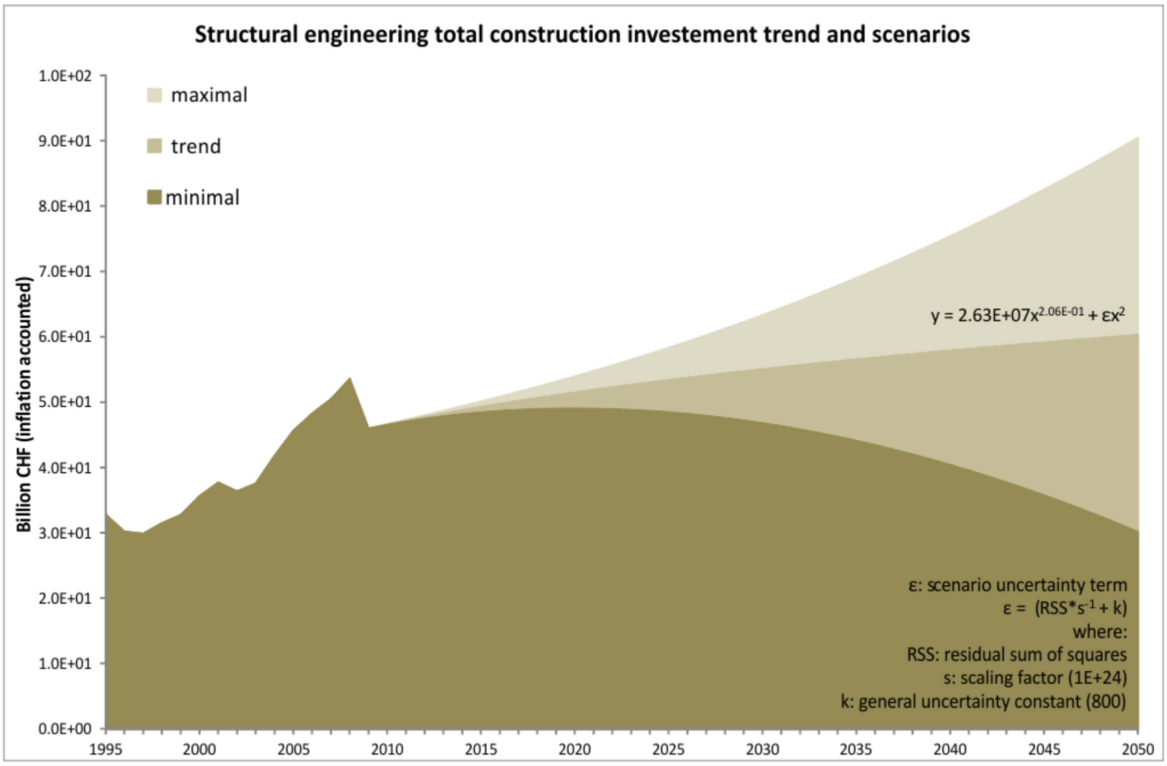

Figure 7: Construction investments trends and scenarios (2008-2050) [Billion CHF]

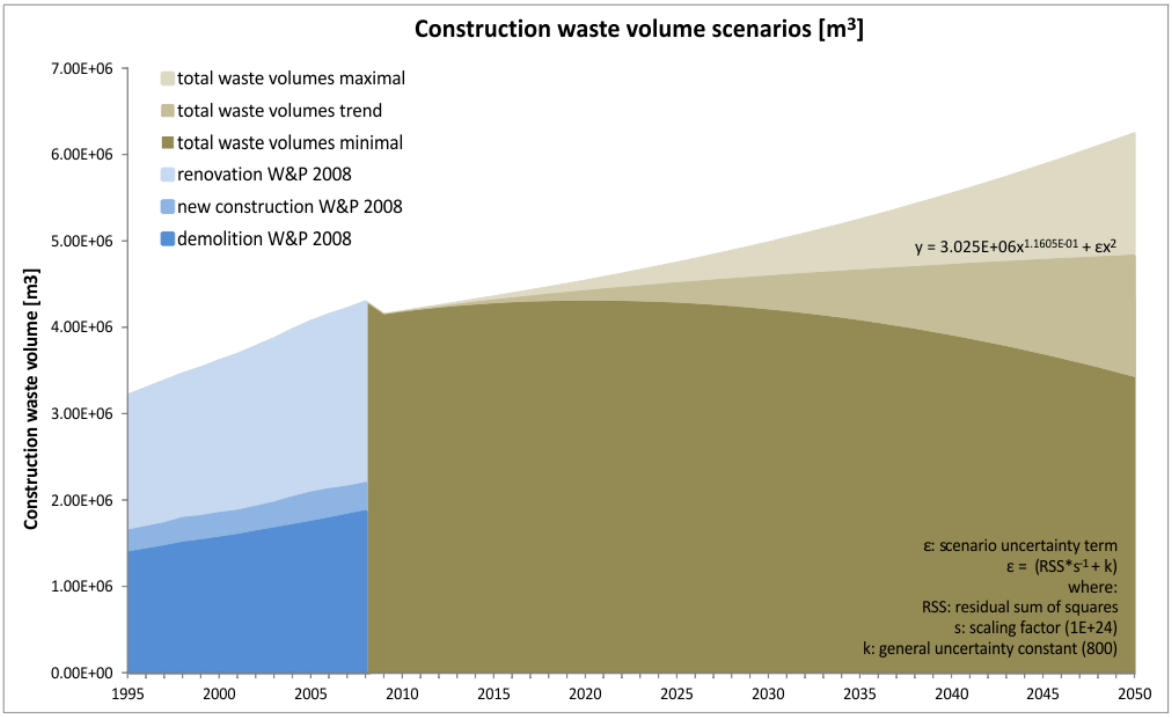

Figure 8: Construction waste trend and scenarios (2008-2050) [m3]

1.3.3. Submodels

Table 5: Detailed pseudo code and mathematical description of the subroutines (commenting lines start with a semicolon)

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
observer (setup)	setup-awarding-authorities	;for each AA type create initial number of AA [set-random-agent-position set awarding-authority-type draw construction-capacity from a normal distribution draw building-radius from a poisson distribution set specification-option-availability set agent selection contact and reference weights set project specification decision parameters set project confirmation decision parameters set tender selection decision parameters]

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
observer (setup)	setup-architects	create initial number of architects [set-random-agent-position draw rmcm-experience from delimited-random-normal (initial RC application / 0.2) draw specification-sensitivity from delimited-random-normal (0.5, 0.2) set project recommendation decision parameters [draw all parameter from delimited-random-normal distributions if price sensitive [adjust price criteria according to market price] if image sensitive [adjust image criteria according to global image]]]
observer (setup)	setup-engineers	create initial number of engineers [set-random-agent-position draw specification-sensitivity from delimited-random-normal (0.5, 0.2) set design specification decision parameters [draw all parameter from delimited-random-normal distributions if price sensitive [adjust price criteria according to market price]]]
observer (setup)	setup-contractors	create initial number of contractors [set-random-agent-position draw rmcm-experience from delimited-random-normal (initial RC application / 0.2) draw specification-sensitivity from delimited-random-normal (0.5, 0.2) set design specification decision parameters [draw all parameter from delimited-random-normal distributions if price sensitive [adjust price criteria according to market price]]]
observer (setup)	set-random-agent-position	while location assigned false [draw random yx coordinates if no agents at the xy position [move agent to that position and set location assigned true]]
observer (various)	delimited-random-normal	while value-set false [draw value from normal distribution with given mean and StD if value between 0 and 1 [set value-set true]] ;delimits the draw from a random normal distribution near 0 to values between 0 and 1 as required by the multi-criteria decision analysis.

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)

observer (go)	calculate-investments-and-create-projects	set annual construction investment [Mio CHF]
		$i(x) = 2.63E + 4\ (x - 1994)^{0.206} \pm \varepsilon(x - 2008)^2$
		with simulation year x, the scenario uncertainty term $\varepsilon = (RSS \times (s-1) + k)$ and the residual sum of squares RSS, the scaling factor $s = (1E + 24)$ and the general uncertainty constant $k = 800$. Power law trend exploration from historical data 1995 – 2008 and investment scenarios after 2008.
		set private-investment = i (x) * private-investment-fraction
		set commercial-investment i (x) * commercial-investment-fraction
		set public-investment i (x) * public-investment-fraction
		for each investment-type (private, commercial and public) [
		  while [investment > 0] [
		    create one project [
		      set construction-year current year
		      set investor type
		      while [sum-set = false][
		        set construction-sum random-normal mean, StD according to investor type
		        if construction-sum > remaining investment [to the remaining money]
		        if construction-sum > 0 [set sum-set true]] ; ensure positive investments
		      reduce investment by the construction-sum
		    ]
		  ]
		]

observer (go)	calculate-RC-supply	set annual construction waste volume [m^3] $w(x) = 3.025E + 6\ (x - 1994)^{0.11605} \pm \varepsilon(x - 2008)^2$ with simulation year x, the scenario uncertainty term $\varepsilon = (RSS \times (s-1) + k)$ and the residual sum of squares RSS, the scaling factor $s = (1E + 24)$ and the general uncertainty constant $k = 800$. Power law trend exploration from historical data 1995 – 2008 and waste scenarios after 2008. set annual concrete rubble supply $s_c(x) = w(x) C_c \mathrm{P}_c R$ and annual mixed rubble supply $s_m(x) = w(x) C_m \mathrm{P}_m R$ with the waste fractions [% volume] $C_c = 0.01524, C_m = 0.4444$ and the waste densities [t/m^3] $\mathrm{P}_c = 2.4;\ \mathrm{P}_m = 1.632$

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
observer (go)	distribute-and-execute-projects	;ensure enough construction capacity in the system for all investor types (private, commercial and public) while this year's projects > construction capacity of investors [increase the capacity of a random AA]] ;distribute the projects to the AA and execute for all this year's projects [assign to a random AA with construction capacity and matching investor type [decrement his construction capacity draw the material amount [t] from a normal distribution (mean 252 StD 107) [t/Mio CHF] times the project's construction sum [Mio CHF] if material amount < 0 [set material amount 0] ;avoid negative amounts move project to a free patch in the building radius around AA's location execute the project]]
AA (distribute-and-execute-projects)	execute-project	make-project-specification select-engineer-for-design-specification select-architect-for-project-recommendation make-project-confirmation select 3 closest contractors as potential contractors for tendering ask them to make-an-offer for this-project] make-tender-selection ;deduct the amount of rmcm applied from the available rmcm if still available, RC-;M fraction of RC with mixed rubble aggregates, density 1.9 tons (75% by weight) ;aggregates per m^3 concrete; 10% overdose for RC-C and 20% for RC-M if RC is selected [if enough of both rubble fraction is still available [demand the two fractions] if only mixed rubble is available [demand all RC-M] if only concrete rubble available [demand all RC-C] if both unavailable [demand CC]] assign the material type applied to the project

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
AA (execute-project)	make-project-specification	;if sustainable construction is an option if a random float < specification option availability [multi criteria decision, matrix multiplication $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{SCS} \\ u_{SC} \end{bmatrix} = \begin{bmatrix} utility\ of\ sustainable\ construction\ specification\ (SCS) \\ utility\ of\ conventional\ specification\ (CS) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{SCS,C1} & v_{SCS,C2} & v_{SCS,C3} \\ (1 - v_{SCS,C1}) & (1 - v_{SCS,C2}) & (1 - v_{SCS,C3}) \end{bmatrix}$ $where\ v_{SCS,C1}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ SCS\ option\ regarding\ criterion\ 1 (C1) in\ comparison\ with\ the\ CS$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \end{bmatrix} = \begin{bmatrix} weight\ of\ social\ aspects \\ weight\ of\ economic\ aspects \\ weigt\ of\ ecological\ aspects \end{bmatrix}$ select the option with the highest utility] else [select CS]
AA (execute-project)	select-engineer-for-design-specification	select the 5 closest engineers out of 18 for design-specification get their personal contact values $c(AA_x, Eng_y, t) = \frac{1+\sum_{t=x}^{t=x-exp} Projects\ of\ AA_x Eng_y}{1+\sum_{t=x}^{t=x-exp} Projects\ of\ AA_x}$ $where\ exp: agents\ experience\ time$ if sustainable construction was specified [make multi criteria decision $S = VW$ providing the selection vector $S = \begin{bmatrix} s_1 \\ \\ s_n \end{bmatrix} = \begin{bmatrix} selection\ value\ of\ engineer\ 1 \\ \\ selection\ value\ of\ engineer\ n \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{S1,C1} & v_{S1,C2} \\ \\ v_{Sn,C1} & v_{Sn,C2} \end{bmatrix}$ $including\ the\ engineers`\ personal\ contact\ values\ v_{Sy,C1} = c(AA_x, Eng_y, t)\ , and$ $theirs`\ sustainable\ construction\ experience\ values\ v_{Sy,C2}$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \end{bmatrix} = \begin{bmatrix} weight\ of\ personal\ contact \\ weight\ of\ sustainable\ construction\ references \end{bmatrix}$ ask the engineer with the maximum value to make-design-specification] else [ask the engineer with the maximum contact value to make-design-specification]

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
Engineer (select-engineer-for-design-specification)	make-design-specification	if (SCS specified by the AA and a random float < specification sensitivity) or (random float < specification-probability (10%)) [make multi criteria decision $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ op$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \end{bmatrix} = \begin{bmatrix} weight\ of\ AA`s\ project\ specification \\ weight\ of\ expected\ tender\ price \\ weight\ of\ experience \\ weight\ of\ standards\ and\ norms \end{bmatrix}$ set design specification to the option with the highest utility u_i] else [set design specification to CC]
AA (execute-project)	select-architect-for-project-recommendation	select the 5 closest architects out of 46 for project-recommendation get their personal contact values $c(AA_x, Arch_y, t) = \frac{1+\sum_{t=x}^{t=x-exp} Projects\ of\ AA_x Arch_y}{1+\sum_{t=x}^{t=x-exp} Projects\ of\ AA_x}$ $where\ exp: agents\ experience\ time$ if sustainable construction was specified [make multi criteria decision $S = VW$ providing the selection vector $S = \begin{bmatrix} s_1 \\ \\ s_n \end{bmatrix} = \begin{bmatrix} selection\ value\ of\ architect\ 1 \\ \\ selection\ value\ of\ architect\ n \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{S1,C1} & v_{S1,C2} \\ & \\ v_{Sn,C1} & v_{Sn,C2} \end{bmatrix}$ $including\ the\ architects`\ personal\ contact\ values\ v_{Sy,C1} = c(AA_x, Arch_y, t)\ , and$ $theirs`\ rmcm\ experience\ values\ v_{Sy,C2}$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \end{bmatrix} = \begin{bmatrix} weight\ of\ personal\ contact \\ weight\ of\ rmcm\ references \end{bmatrix}$ ask the architect with the maximum value to make-project-recommendation] else [ask the architect with the maximum contact value to make-project-recommendation]

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
Architect (select-architect-for-project-recommendation)	make-project-recommendation	if ((SCS is specified by the AA or RC by the architect) and (random float < specification sensitivity)) or (random float < specification-probability (10%)) [make multi criteria decision $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} & v_{RC,C5} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) & (1 - v_{RC,C5}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ op$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \\ w_{C5} \end{bmatrix} = \begin{bmatrix} weight\ of\ AA`s\ project\ specification \\ weight\ of\ expected\ tender\ price \\ weight\ of\ engineer`s\ design\ specification \\ weight\ of\ rmcm\ image \\ weight\ of\ asthetical\ aspects \end{bmatrix}$ recommend the option with the highest utility u_i] else [recommend CC]
AA (execute-project)	make-project-confirmation	if (SCS specified by the AA) or (RC by the architect or the engineer) [make multi criteria decision $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ op$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \end{bmatrix};\ W(private\ AA) \begin{bmatrix} weight\ of\ Architect`s\ project\ recommendation \\ weight\ of\ expected\ tender\ price \\ weight\ of\ technical\ aspects \\ weight\ of\ ecological\ aspects \end{bmatrix}$ $W(commercial\ AA) \begin{bmatrix} weight\ of\ Architect`s\ project\ recommendation \\ weight\ of\ economic\ aspects \\ weight\ of\ technical\ aspects \\ weight\ of\ ecological\ aspects \end{bmatrix}$ $W(public\ AA) \begin{bmatrix} weight\ of\ Architect`s\ project\ recommendation \\ weight\ of\ expected\ price \\ weight\ of\ political\ aspects \\ weight\ of\ rmcm\ image \end{bmatrix}$ set project confirmation to the option with the highest utility u_i] else [set project confirmation to CC]

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
Contractors (execute-project)	make-an-offer	if (RC specified in the tender documents) or (random float < specification-probability (10%)) and recycled aggregates are still available [make multi criteria decision $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ op$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \end{bmatrix} = \begin{bmatrix} weight\ of\ project\ confirmation\ (tender\ documents) \\ weight\ of\ economic\ aspects \\ weight\ of\ experience \\ weight\ of\ technical\ aspects \end{bmatrix}$ set tender material type to the option with the highest utility u_i] else [set tender material type to CC] ;set tender price according to the chosen material and the global price difference if tender material is RC [draw the tender-price from a delimited-random-normal distribution with the mean (0.5 - Percental-RCtoCC-price-difference) and the StD 0.05] else [draw the tender-price from a delimited-random-normal distribution with the mean (0.5 + Percental-RCtoCC-price-difference) and the StD 0.05] ;since prices are not real prices but a normalized price comparison a negative ;Percental-RCtoCC-price-difference results in a higher/better tender-price value
AA (execute-project)	make-tender-selection	if rmcm are specified in one of the tenders [for all potential-contractors [if public AA [change criterium-4 to rmcm-experience] calculate their tender utility $U = VW$ providing the utility vector $U = \begin{bmatrix} u_{RC} \\ u_{CC} \end{bmatrix} = \begin{bmatrix} utility\ of\ recycled\ concrete\ (RC) \\ utility\ of\ conventional\ concrete\ (CC) \end{bmatrix}$ by multiplying the option value matrix $V = \begin{bmatrix} v_{RC,C1} & v_{RC,C2} & v_{RC,C3} & v_{RC,C4} \\ (1 - v_{RC,C1}) & (1 - v_{RC,C2}) & (1 - v_{RC,C3}) & (1 - v_{RC,C4}) \end{bmatrix}$ $where\ v_{RC,Ci}\ is\ the\ normalized\ (\ between\ 0\ and\ 1)\ performance$ $of\ the\ RC\ option\ regarding\ criterion\ i(Ci) in\ comparison\ with\ the\ CC\ op$ with the criteria weight vector $W = \begin{bmatrix} w_{C1} \\ w_{C2} \\ w_{C3} \\ w_{C4} \end{bmatrix} =$ $\begin{bmatrix} weight\ of\ project\ confirmation\ (tender\ documents) \\ weight\ of\ tender\ price \\ weight\ of\ architect`s\ project\ recommendation \\ weight\ of\ ecological_{priv}, marketability\ _{com} or\ image\ _{pub} aspects \end{bmatrix}$] demand the materials offered from the contractor with the highest utility u_i else [demand CC offered from the contractor with the best price]

context (calling procedure)	**subroutine** (NetLogo name)	**description** (equations and/or pseudo-code, comments indicated with a semicolon)
observer (go)	set-global-demand-parameters	set $\text{AmountofCurrentRCApplied} = \sum \text{this year`s projects material amounts with RC }\ [t]$ set $\text{AmountofCurrentCCapplied} = \sum \text{this year`s projects material amounts with CC }\ [t]$ set $\text{CurrentFractionRCApplied} = \frac{\text{AmountofCurrentRCapplied}}{\text{AmountofCurrentRCapplied+ AmountofCurrentCCapplied}}$ set $\text{ProjectFractionRCApplied} = \frac{\sum \text{this year`s projects with RC}}{\sum \text{this year`s projects}}$ [% by number] set $RMCMimage = \text{CurrentFractionRCApplied}$ set $AllTimeRCapplied = AllTimeRCapplied + \text{ AmountofCurrentRCapplied [t]}$ set $AllTimeCCapplied = AllTimeCCapplied + \text{ AmountofCurrentCCapplied } [t]$ set $\text{GlobalFractionRCApplied} = \frac{\text{AllTimeRCapplied}}{\text{AllTimeRCapplied+AllTimeCCapplied}}$ [% by mass]
observer (go)	update-awarding-authorities	for private AA [;set probabilistic building for private AA draw new construction-capacity from delimited-random-normal distribution if random-float 1 < construction-capacity [set projects-to-do 1] else [set projects-to-do 0]] for commercial and public AA [reset projects-to-do to construction capacity] for public AA [draw image parameter from delimited-random-normal distribution with the global RMCM-image and a StD of 0.15]
observer (go)	update-architect-properties	;update rmcm-experience according to the materials applied in the last years (agents-experience-time), experience is used for the architect selection for all architects [if any projects done at all then adjust the rmcm-experience [$exp(x) = \exp(x-1)\left(\frac{1+\left(\frac{\sum matarials\ applied\ in\ my\ projects\ with\ RC}{\sum matarials\ applied\ in\ all\ my\ projects}\right)}{1+inital\ RC\ application\ fraction}\right)$ $this\ is,\ a\ stable\ RC\ application\ keeps\ the\ architects`\ experience\ stable$ delimit the experience to < 1]]

<table>
<tr><th>context (calling procedure)</th><th>subroutine (NetLogo name)</th><th>description
(equations and/or pseudo-code, comments indicated with a semicolon)</th></tr>
<tr><td>observer (go)</td><td>update-engineer-properties</td><td>;update design-specification-experience according to the materials applied in the last years (agents-experience-time)
for all engineers [
if any projects done at all then adjust the design specification experience [
$$exp(x) = \exp(x-1)\left(\frac{1+\frac{1}{EmpExp}w_{exp}\left(\frac{\sum matarials\ applied\ in\ my\ projects\ with\ RC}{\sum matarials\ applied\ in\ all\ my\ projects}\right)}{1+inital\ RC\ application\ fraction}\right)$$
$where: EmpExp\ is\ the\ mean\ experience\ found\ in\ the\ survey$
$w_{exp}\ is\ the\ individual\ engineers`\ experience\ weight$
This is, already RC experienced agents adjust slower and those giving more importance on the experience adjust quicker. Since the mean initial experience and the mean experience weight are in the same range on a population level they compensate.
delimit the experience to < 1
]
]</td></tr>
<tr><td>observer (go)</td><td>update-contractor-properties</td><td>;update tender-submission-experience according to the materials applied in the last years (agents-experience-time)
for all contractors [
if any projects done at all then adjust the tender submission experience [
$$exp(x) = \exp(x-1)\left(\frac{1+\frac{1}{EmpExp}w_{exp}\left(\frac{\sum matarials\ applied\ in\ my\ projects\ with\ RC}{\sum matarials\ applied\ in\ all\ my\ projects}\right)}{1+inital\ RC\ application\ fraction}\right)$$
$where: EmpExp\ is\ the\ mean\ experience\ found\ in\ the\ survey$
$w_{exp}\ is\ the\ individual\ contractors`\ experience\ weight$
This is, already RC experienced agents adjust slower and those giving more importance on the experience adjust quicker. Since the mean initial experience and the mean experience weight are in the same range on a population level they compensate.
delimit the experience to < 1
]
]</td></tr>
</table>

2. Part II: Supplementary simulation results information

2.1. Supporting Figures

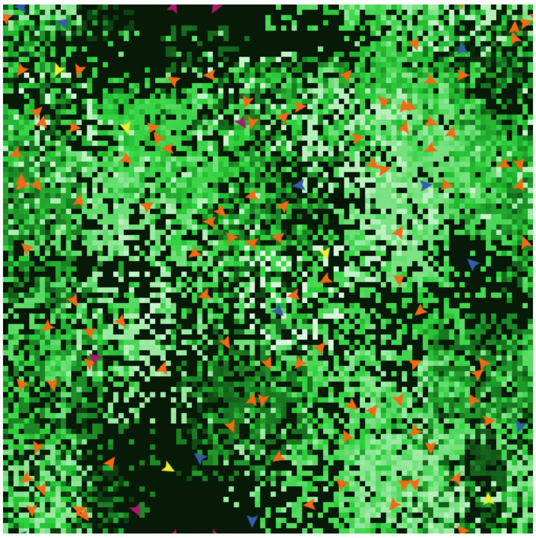

Figure 9: Exemplified model view of a spatial demand pattern (the brighter the green the higher the demand for recycling materials) **from the simplest model version implemented (simple 0.1)**

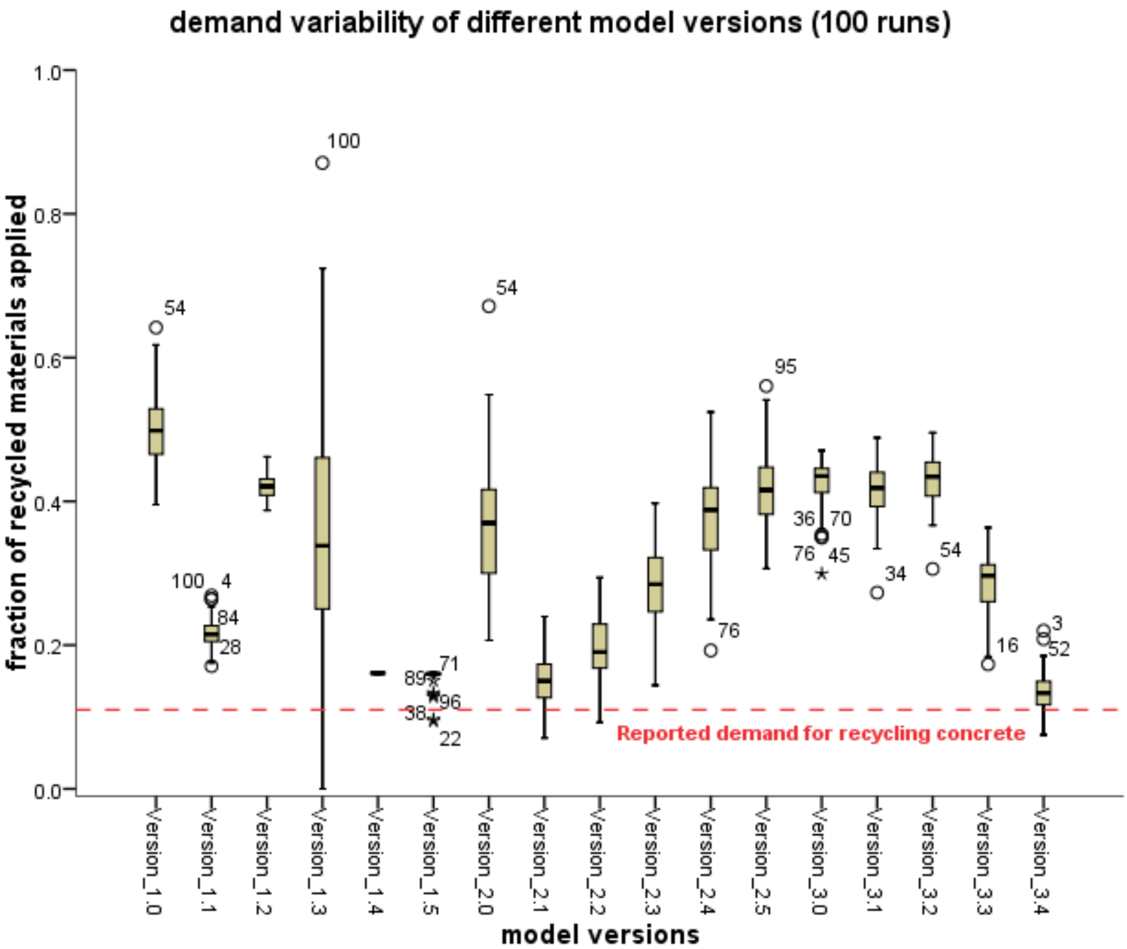

Figure 10: Boxplot of the demand distribution measured by the fraction of recycling materials applied of different model versions in comparison with the reported fraction for the current demand.

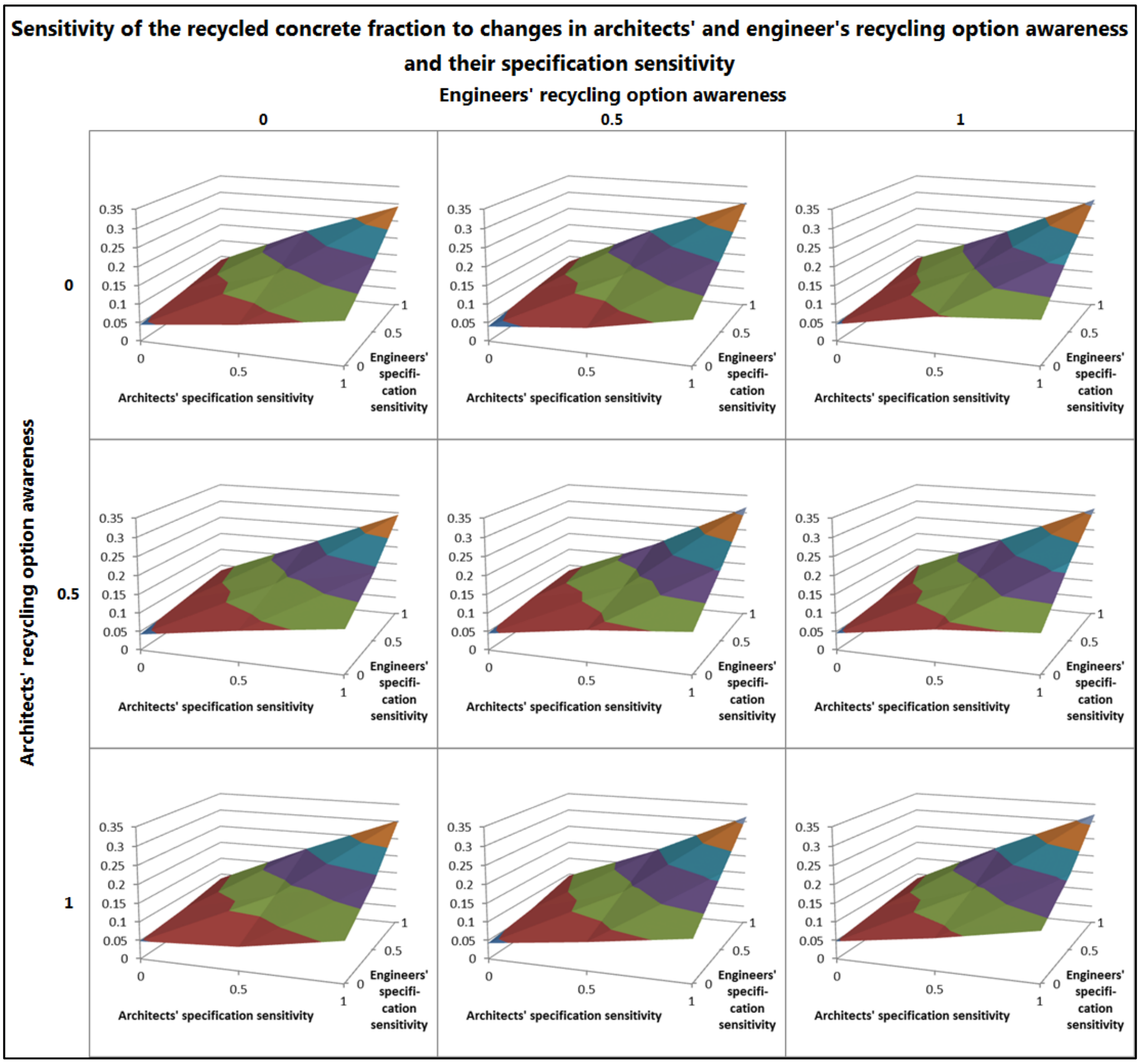

Figure 11: Sensitivity of the fraction of recycled concrete applied to changes in architects` and engineers` recycling option awareness and their specification sensitivity (Architects' and engineers' option awareness is increased from graph to graph, while their sensitivity to previous actors specifications is displayed within each graph, the recycled concrete fraction represents mean values from 20 runs)

2.2. Supporting Tables

Table 6: Structural engineering C&D waste in % [m3] per waste origin (Data: FOEN (2008))

Waste origin	Demolition	New construction	Maintenance	Total	Concrete rubble	Mixed rubble
Concrete	24.8%	13.8%	7.8%	**15.24%**	**15.24%**	
Roads rubble	19.6%	26.2%	8.2%	**14.17%**		
Brick works	31.3%	8.4%	10.7%	**19.01%**		**44.4%**
Mineral fraction	5.8%	5.3%	16.4%	**11.22%**		
Asphalt	1.0%	1.0%	2.5%	1.76%		
Combustible materials	6.3%	22.5%	33.3%	21.41%		
Wood	7.8%	22.2%	19.1%	14.68%		
Metals	0.6%	0.8%	2.0%	1.34%		
Mixed materials	2.8%	0.0%	0.0%	1.17%		

Table 7: Construction waste density in [t/m3] per waste origin (Data: FOEN (2008))

Waste origin	Demolition	New construction	Maintenance	Total	Concrete rubble	Mixed rubble
Concrete	2.400	2.400	2.400	**2.400**	**2.400**	
Roads rubble	1.600	1.600	1.600	**1.600**		
Brick works	1.502	1.507	1.530	**1.511**		**1.632**
Mineral fraction	1.711	1.854	1.926	**1.878**		
Asphalt	1.600	1.600	1.600	1.600		
Combustible materials	0.125	0.127	0.189	0.176		
Wood	0.473	0.578	0.581	0.557		
Metals	6.515	6.171	5.623	5.798		
Mixed materials	1.600			1.600		

3. Part III: References to supporting information

BfS. (2008). Bau- und Wohnbaustatistik [Building and construction statistics]. *annually*.

Davis, M. A., & Heathcote, J. (2005). Housing and the business cycle. [Article]. *International Economic Review, 46*(3), 751-784.

FOEN. (2001a). *Bauabfälle Schweiz - Mengen, Perspektiven und Entsorgungswege. Band 1: Kennwerte [Construction and demolition waste in Switzerland - amounts, perspectives and disposal routes. Volume 1: Statistical values].* Bern: Federal Office for the Environment (FOEN).

FOEN. (2001b). *Bauabfälle Schweiz - Mengen, Perspektiven und Entsorgungswege. Band 2: Kantonale Werte [Construction and demolition waste in Switzerland - amounts, perspectives and disposal routes. Volume 2: Cantonal values].* Bern: Federal Office for the Environment (FOEN).

FOEN. (2008). *Bauabfaelle Hochbau in der Schweiz; Ergebnisse der Studie 2008 [Swiss buildings` construction waste; Results from a 2008 study)*. Bern, Switzerland: Federal Office for the Environment.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., et al. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling, 198*(1-2), 115-126.

Grimm, V., Berger, U., Deangelis, D., Polhill, G. J., Giske, J., & Railsback, S. F. (2010). The ODD protocol: a review and first update. *Ecological Modelling, 221*.

Knoeri, C., Binder, C. R., & Althaus, H. J. (2011a). An agent operationalization approach for context specific agent-based modeling. *JASSS The Journal of Artificial Societies and Social Simulation, 14*(2).

Knoeri, C., Binder, C. R., & Althaus, H. J. (2011b). Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials. *Resources, Conservation and Recycling, 55*(11), 1039-1050.

Knoeri, C., Sanyé-Mengual, E., & Althaus, H. J. (2012). Comparative LCA of recycled and conventional concrete for structural applications. [in press]. *International Journal of Life Cycle Assessment*.

Lichtensteiger, T. (2006). *Bauwerke als Ressourcennutzer und Ressourcenspender, in der langfristigen Entwicklung urbaner Systeme; Ein Beitrag zur Exploration urbaner Lagerstätten [Buildings as resource consumer and source in a long term perspective of urban systems; a contribution to urban stock exploration]*. Zürich: vdf Hochschulverlag AG an der ETH Zürich.

Mauch, U., & Scheidegger, A. (1996). *Nachhaltigkeit des Bauens in der Schweiz [Sustainability of construction works in Switzerland]*. Bern: ENET.

Railsback, S. F. (2001). Concepts from complex adaptive systems as a framework for individual-based modelling. [Article]. *Ecological Modelling, 139*(1), 47-62.

Saaty, T. L. (1980). *The analytical hierarchy process: planning, priority setting, resource allocation*. New York: McGraw-Hill.

Saaty, T. L. (1990). How to Make a Decision - the Analytic Hierarchy Process. *European Journal of Operational Research, 48*(1), 9-26.

Suarezvilla, L., & Hasnath, S. A. (1993). The effect of infratsructure on invention - innovative capacity and the dynamics of public construction market. *Technological Forecasting and Social Change, 44*(4), 333-358.

Wilensky, U. (1999). NetLogo. Northwestern University, Evanston, IL: Center for Connected Learning and Computer-Based Modeling. http://ccl.northwestern.edu/netlogo .

Supporting information to publication IV

Comparative LCA of recycled and conventional concrete for structural applications

Knoeri Christof [a,c], Sanyé-Mengual Esther [b], Althaus Hans-Joerg [a]

[a)] *Technology and Society Laboratory, Empa, Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland*

[b)] *Sostenipra (ICTA-IRTA-Inèdit) – Institute of Environmental Science and Technology. Universitat Autonoma de Barcelona (UAB). Campus de la UAB, 08193. Cerdanyola del Vallès, Spain.*

[C)] *Sustainability Research Institute, School of Earth & Environment, University of Leeds*

Table of content

List of tables

List of figures

Table 1 Concrete properties and minimum amount of cement by application [according to SN EN 206-1 (Appendix F) (2002)]

Application (own specifications and NPK class)	Exposition class	Comprehensive strength class	Minimum cement content (kg/m^3)	Maximum water-cement ratio	Uses exemplified
Outdoor concrete (OC) (NPK C)	XC3/4	C30/37	300	0.50 – 0.55	Basement, garage, floors, exterior walls
Indoor concrete (IC) (NPK A/B)	XC1	C25/30	280	0.60 - 0.65	Indoor walls, ceilings
Lean concrete (LC)	XC0	-	50	-	Blinding concrete, subbases

Table 2 Aggregates composition of mixed and concrete rubble aggregates (Rubli 2011; Hoffmann 2007)

Composition distribution	Mixed rubble aggregates (%)	Concrete rubble aggregates (%)
Natural grains (R_u)	20	10
Concrete grains (R_c)	60	90
Clay grains (R_b)	20	0

Table 3 Composition of concrete and mixed rubble (Fractions distribution Eberhard (2011) and FOEN (2001), iron content (Doka 2007) and foreign substances content (Hächler 2005))

Type of rubble	Fractions distribution (M.%)			Other substances content (M.%)	
	Waste concrete not reinforced	Waste reinforced concrete	Waste brick	Foreign substances	Iron
Concrete rubble	28.5	66.5	5	0.26	2
Mixed rubble	21	49	30	0.72	1.47

Table 4 Reference distances and transport scenarios, by element and transport stage (Reference distances from average data in bold (Gschoesser 2011) and reference, best and worst case scenarios for C&D waste to recycling plant and landfill, recycled aggregates and concrete to construction site)

index	Transported element	Transport stages		Reference distances (km)			Transport-scenarios	
							Best case for RC	Worst case for RC
		From	To	Lorry28t	Rail	Ship	Lorry 28t	Lorry 28t
T1	**Natural aggregates**	Gravel pit	Concrete plant	**15**	25	3		
T2	**Cement**	Cement plant	Concrete plant	**20**	55	0		
T3	**Additive**	Additive plant	Concrete plant	**85**				
T4	**Filler (fly ash)**		Concrete plant	**50**				
T5	**C&D waste**	Demolition	Recycling plant	15 [a, b]	[c]		5	25
T6	**Rec. aggregates**	Recycling plant	Concrete plant	0			0	15
T7	**Concrete**	Concrete plant	Construction site	15			5	25
T8	**C&D waste**	Demolition	Landfill	30 [b]			60	15

[a] Although the average distance was 17 km (Gschösser, 2011), for comparability reasons in the analysis the 15 km from ecoinvent database were considered . [b] Since landfills are further away of the large C&D waste sources than recycling plants, the corresponding transport distances are higher (Gschösser, 2011; Eberhard, 2011; Rubli, 2011). [c] Rail distance for recycled aggregates is neglected, as it is only 0.4 km (Gschösser, 2011).

Table 5 Life Cycle Inventories (LCI) for outdoor concrete mixtures, by option and recycling scenario

INPUTS	Unit	Outdoor concrete (OC)												
		CC	RC-C (min)			RC-C (ref)			RC-M (min)			RC-M (ref)		
Denomination [a]		OC CC	OC RC-Cmin CEM300	OC RC-Cmin CEM310	OC RC-Cmin CEM320	OC RC-Cref CEM300	OC RC-Cref CEM310	OC RC-Cref CEM320	OC RC-Mmin CEM300	OC RC-Mmin CEM320	OC RC-Mmin CEM340	OC RC-Mref CEM300	OC RC-Mref CEM330	OC RC-Mref CEM360
Component														
Natural aggregates (Gravel, round)	kg	1890	1284.48			893.2			1068.2			687		
Recycling aggregates, from concrete rubble	kg	0	499.52			730.8			0			0		
Recycled aggregates, from mixed rubble	kg	0	0			0			457.8			687		
Cement Portland (Z42.5 or calcareous)	kg	300	300	310	320	300	310	320	300	320	340	300	330	360
Water (Tap water)	kg	105	105	110	120	115	120	130	130	155	170	140	160	180
Additive (Superplasticizer - Chemicals organic)	kg	3.30	3.9	4.03	4.16	3.9	4.03	4.16	3.9	4.16	4.42	3.9	4.29	4.68
Filler (fly ash) (Avoided disposal, separator sludge)	kg	- 20	-20	-20.7	-21.3	-20	-20.7	-21.3	-20	-21.3	-22.7	-20	-22	-24
Transport														
Cement (lorry 20-28t, 20 km)	tkm	6	6	6.2	6.4	6	6.2	6.4	6	6.4	6.8	6	6.6	7.2
Cement (train, 55 km)	tkm	16.5	16.5	17.1	17.6	16.5	17.1	17.6	16.5	17.6	17.2	16.5	18.2	19.2
Additive (Superplasticizer) (lorry 20-28t, 85 km)	tkm	0.281	0.332	0.343	0.354	0.332	0.343	0.354	0.332	0.354	0.376	0.332	0.365	0.398
Filler (fly ash) (lorry 20-28t, 50 km)	tkm	1	1	1.03	1.07	1	1.03	1.07	1	1.07	1.13	1	1.1	1.2
Concrete to construction site (lorry 20-28t, 15 km)	tkm	34.8	33.2	35.4	37.6	30.9	31.2	31.5	29.7	30.4	30.9	27.6	28.4	29.1
Natural aggregates (barge, 3 km)	tkm	5.67	3.85			2.68			3.2			2.06		
Natural aggregates (lorry 20-28t, 15 km)	tkm	28.4	19.1			13.4			16			10.3		
Natural aggregates (train, 25 km)	tkm	47.3	32.1			22.3			26.7			17.2		
C&D waste to recycle (lorry 20-28t, 15 km)	tkm	0	7.49			11			6.87			10.3		
Recycled aggregates (lorry 20-28t, 0 km)	tkm	0	0			0			0			0		
C&D waste to landfill (Avoided, lorry 20-28t, 30 km)	tkm	0	-15			-21.9			-13.7			-20.6		
Diesel (train, 50 km)	tkm	2.66E-02												
Waste (lorry 3.5-20t, 20 km)	tkm	3.40E-01												
Infrastructure and maintenance														
Concrete mixing factory	unit	4.57E-07												
Lubricating oil	kg	1.19E-02												
Steel, low-alloyed, hot rolled	kg	2.38E-02												
Synthetic rubber	kg	7.13E-03												
Energy consumption														
Heat, central or small-scale, other than natural gas	MJ	12.6												
Heat, district or industrial, other than natural gas	MJ	2.94												
Heat, district or industrial, natural gas	MJ	1.04												
Electricity, medium voltage	kWh	4.36												
Diesel, burned in building machine	MJ	22.7												
OUTPUTS														
Production wastes treatment														
Wastewater from concrete production	m^3	1.43E-02												
Municipal solid waste, 22.9% water	kg	9.51E-02												
Waste concrete, 5% water	kg	16.9												
Heat, waste	MJ	15.7												
Concrete	m^3	**1**												

[a] Since two types of cement (i.e. Portland cement CEM I 42.5 and Portland calcareous CEM II) are investigated, the denominations are extended with the cement considered (e.g. IC-CC Portland 42.5 or IC-CC Portland calcareous)

Table 6 Life Cycle Inventories (LCI) for indoor concrete mixtures, by option, recycling scenario and life cycle stage

INPUTS	Unit	Indoor concrete (IC)												
		CC	RC-C (min)			RC-C (ref)			RC-M (min)			RC-M (ref)		
Denomination [a]		IC CC	IC RC-Cmin CEM280	IC RC-Cmin CEM290	IC RC-Cmin CEM300	IC RC-Cref CEM280	IC RC-Cref CEM290	IC RC-Cref CEM300	IC RC-Mmin CEM280	IC RC-Mmin CEM305	IC RC-Mmin CEM330	IC RC-Mref CEM280	IC RC-Mref CEM310	IC RC-Mref CEM340
Component														
Natural aggregates (Gravel, round)	kg	1890	1284.48			893.2			1068.2			687		
Recycling aggregates, from concrete rubble	kg	0	499.52			730.8			0			0		
Recycled aggregates, from mixed rubble	kg	0	0			0			457.8			687		
Cement Portland (Z42.5 or calcareous)	kg	280	280	290	300	280	290	300	280	305	330	280	310	340
Water (Tap water)	kg	120	120	125	135	130	135	140	130	155	170	140	160	180
Additive (Superplasticizer - Chemicals organic)	kg	1.12	1.68	1.74	1.8	1.68	1.74	1.8	1.68	1.83	1.98	1.68	1.86	2.04
Filler (fly ash) (Avoided disposal, separator sludge)	kg	- 10	-10	-10.4	-10.7	-10	-10.4	-10.7	-10	-10.9	-11.8	-10	-11.1	-12.1
Transport														
Cement (lorry 20-28t, 20 km)	tkm	5.6	5.6	5.8	6	5.6	5.8	6	5.6	6.1	6.6	5.6	6.2	6.8
Cement (train, 55 km)	tkm	15.4	15.4	16	16.5	15.4	16	16.5	15.4	16.8	17.2	15.4	17.1	18.7
Additive (Superplasticizer) (lorry 20-28t, 85 km)	tkm	9.52E-02	0.143	0.148	0.153	0.143	0.156	0.168	0.143	0.156	0.168	0.143	0.158	0.173
Filler (fly ash) (lorry 20-28t, 50 km)	tkm	0.5	0.5	0.518	0.536	0.5	0.518	0.536	0.5	0.544	0.589	0.5	0.553	0.607
Concrete to construction site (lorry 20-28t, 15 km)	tkm	34.5	32.9	33.2	33.5	30.7	30.9	31.1	29.2	30	30.6	27.1	27.9	28.6
Natural aggregates (barge, 3 km)	tkm	5.67	3.85			2.68			3.2			2.06		
Natural aggregates (lorry 20-28t, 15 km)	tkm	28.4	19.1			13.4			16			10.3		
Natural aggregates (train, 25 km)	tkm	47.3	32.1			22.3			26.7			17.2		
C&D waste to recycle (lorry 20-28t, 15 km)	tkm	0	7.49			11			6.87			10.3		
Recycled aggregates (lorry 20-28t, 0 km)	tkm	0	0			0			0			0		
C&D waste to landfill (Avoided, lorry 20-28t, 30 km)	tkm	0	-15			-21.9			-13.7			-20.6		
Diesel (train, 50 km)	tkm	2.66E-02												
Production waste (lorry 3.5-20t, 20 km)	tkm	3.40E-01												
Infrastructure and maintenance														
Concrete mixing factory	unit	4.57E-07												
Lubricating oil	kg	1.19E-02												
Steel, low-alloyed, hot rolled	kg	2.38E-02												
Synthetic rubber	kg	7.13E-03												
Energy consumption														
Heat, central or small-scale, other than natural gas	MJ	12.6												
Heat, district or industrial, other than natural gas	MJ	2.94												
Heat, district or industrial, natural gas	MJ	1.04												
Electricity, medium voltage	kWh	4.36												
Diesel, burned in building machine	MJ	22.7												
OUTPUTS														
Production wastes treatment														
Wastewater from concrete production	m^3	1.43E-02												
Municipal solid waste, 22.9% water	kg	9.51E-02												
Waste concrete, 5% water	kg	16.9												
Heat, waste	MJ	15.7												
Concrete	m^3	**1**												

[a] Since two types of cement (i.e. Portland cement CEM I 42.5 and Portland calcareous CEM II) are investigated, the denominations are extended with the cement considered (e.g. IC-CC Portland 42.5 or IC-CC Portland calcareous)

Table 7 Life Cycle Inventories (LCI) for lean concrete mixtures, by option, recycling scenario and life cycle stage

INPUTS	Unit	Lean concrete (LC) CC		Lean concrete (LC) RC	
Denomination		LC CC CEM150	LC CC CEM200	LC RC CEM150	LC RC CEM200
Component					
Natural aggregates (Gravel, round)	kg	1890		0	
Recycling aggregates, from concrete rubble	kg	0		0	
Recycled aggregates, from mixed rubble	kg	0		1890	
Cement Portland Calcareous	kg	150	200	150	200
Water (Tap water)	kg	120	155	140	175
Additive (Superplasticizer - Chemicals organic)	kg	0.3	0.4	0.6	0.8
Filler (fly ash) (Avoided disposal, separator sludge)	kg	0	0	0	0
Transport					
Cement (lorry 20-28t, 20 km)	tkm	3	4	3	4
Cement (train, 55 km)	tkm	8.25	11	8.25	11
Additive (Superplasticizer) (lorry 20-28t, 85 km)	tkm	2.55E-02	3.40E-02	5.10E-02	6.80E-02
Filler (fly ash) (lorry 20-28t, 50 km)	tkm	0	0	0	0
Concrete to construction site (lorry 20-28t, 15 km)	tkm	32.4	32.7	22.7	24
Natural aggregates (barge, 3 km)	tkm	5.67		0	
Natural aggregates (lorry 20-28t, 15 km)	tkm	38.4		0	
Natural aggregates (train, 25 km)	tkm	47.3		0	
C&D waste to recycle (lorry 20-28t, 15 km)	tkm	0		18.3	
Recycled aggregates (lorry 20-28t, 0 km)	tkm	0		0	
C&D waste to landfill (Avoided, lorry 20-28t, 30 km)	tkm	0		-38.6	
Diesel (train, 50 km)	tkm	2.66E-02			
Waste (lorry 3.5-20t, 20 km)	tkm	3.40E-01			
Infrastructure and maintenance					
Concrete mixing factory	unit	4.57E-07			
Lubricating oil	kg	1.19E-02			
Steel, low-alloyed, hot rolled	kg	2.38E-02			
Synthetic rubber	kg	7.13E-03			
Energy consumption					
Heat, central or small-scale, other than natural gas	MJ	12.6			
Heat, district or industrial, other than natural gas	MJ	2.94			
Heat, district or industrial, natural gas	MJ	1.04			
Electricity, medium voltage	kWh	4.36			
Diesel, burned in building machine	MJ	22.7			
OUTPUTS					
Production wastes treatment					
Wastewater from concrete production	m^3	1.43E-02			
Municipal solid waste, 22.9% water	kg	9.51E-02			
Waste concrete, 5% water	kg	16.9			
Heat, waste	MJ	15.7			
Concrete	**m^3**	**1**			

Table 8 Minimum and reference scenario environmental benefits (Ecological Scarcity, Ecoindicator, GWP and ADP) for recycled options, by application and recycled concrete type for Portland Cement 42.5 mixtures, CEM1 indicates equal cement amount as CC, CEM2 the medium additional cement scenario (e.g. CEM310 for OC) and CEM3 the maximum additional cement scenario (e.g. CEM340 for IC RC-Mref)

	Application	**Outdoor concrete (OC)**				**Indoor concrete (IC)**				
	CEM scenarios	**RC-C$_{min}$**	**RC-C$_{ref}$**	**RC-M$_{min}$**	**RC-M$_{ref}$**	**RC-C$_{min}$**	**RC-C$_{ref}$**	**RC-M$_{min}$**	**RC-M$_{ref}$**	**Mean** (across mixtures and applications)
Ecological Scarcity (MPt)	*CC Value*	2.27E+05		2.27E+05		2.17E+05		2.17E+05		
	CEM1	1.73E+05	1.44E+05	1.72E+05	1.45E+05	1.63E+05	1.33E+05	1.61E+05	1.34E+05	
	CEM2	1.78E+05	1.48E+05	1.81E+05	1.59E+05	1.68E+05	1.38E+05	1.73E+05	1.48E+05	
	CEM3	1.83E+05	1.53E+05	1.91E+05	1.73E+05	1.73E+05	1.43E+05	1.85E+05	1.62E+05	
	Mean reduction (%)	***21.53***	***34.72***	***20.2***	***30.12***	***22.58***	***36.40***	***20.23***	***3.63***	***27.0***
	SD	*2.07*	*2.08*	*4.14*	*6.21*	*2.16*	*2.15*	*5.38*	*6.46*	*7.5*
Ecoindicator (Pt)	*CC Value*	9.76E+00		9.76E+00		9.80E+00		9.80E+00		
	CEM1	6.85E+00	5.30E+00	7.09E+00	5.70E+00	6.88E+00	5.33E+00	7.12E+00	5.73E+00	
	CEM2	7.07E+00	5.53E+00	7.55E+00	6.39E+00	7.12E+00	5.57E+00	7.73E+00	6.46E+00	
	CEM3	7.31E+00	5.76E+00	8.00E+00	7.07E+00	7.37E+00	5.82E+00	8.34E+00	7.20E+00	
	Mean reduction (%)	***27.52***	***43.36***	***22.69***	***34.59***	***27.34***	***45.13***	***21.17***	***34.08***	***32.1***
	SD	*2.35*	*2.36*	*4.66*	*6.99*	*2.51*	*2.49*	*6.24*	*7.51*	*9.3*
GWP (kg CO_2 eq.)	*CC Value*	2.78E+02		2.78E+02		2.57E+02		2.57E+02		
	CEM1	2.54E+02	2.41E+02	2.57E+02	2.47E+02	2.33E+02	2.20E+02	2.37E+02	2.26E+02	
	CEM2	2.63E+02	2.50E+02	2.75E+02	2.73E+02	2.42E+02	2.29E+02	2.58E+02	2.51E+02	
	CEM3	2.71E+02	2.58E+02	2.92E+02	2.98E+02	2.50E+02	2.37E+02	2.79E+02	2.77E+02	
	Mean reduction (%)	***5.57***	***10.09***	***1.10***	***1.77***	***6.09***	***10.99***	***-0.31***	***2.21***	***4.7***
	SD	*3.08*	*3.08*	*6.17*	*9.24*	*3.28*	*3.27*	*8.20*	*9.83*	*6.8*
ADP (kg Sb eq.)	*CC Value*	7.37E-01		7.37E-01		6.43E-01		6.43E-01		
	CEM1	5.19E-01	4.04E-01	5.61E-01	4.66E-01	4.24E-01	3.09E-01	4.65E-01	3.70E-01	
	CEM2	5.39E-01	4.24E-01	6.01E-01	5.26E-01	4.42E-01	3.26E-01	5.10E-01	4.24E-01	
	CEM3	5.59E-01	4.44E-01	6.41E-01	5.86E-01	4.60E-01	3.44E-01	5.55E-01	4.78E-01	
	Mean reduction (%)	***26.87***	***42.53***	***18.49***	***28.71***	***31.28***	***49.24***	***20.64***	***34.05***	***32.3***
	SD	*2.71*	*2.72*	*5.44*	*8.14*	*2.81*	*2.79*	*7.02*	*8.40*	*10.8*

Table 9 Minimum and reference scenario environmental benefits (Ecological Scarcity, Ecoindicator, GWP and ADP) for recycled options, by application and recycled concrete type for Portland cement calcareous mixtures, CEM1 indicates equal cement amount as CC, CEM2 the medium additional cement scenario (e.g. CEM310 for OC) and CEM3 the maximum additional cement scenario (e.g. CEM340 for IC RC-Mref)

	Application	**Outdoor concrete (OC)**				**Indoor concrete (IC)**				
	CEM scenarios	**RC-C$_{min}$**	**RC-C$_{ref}$**	**RC-M$_{min}$**	**RC-M$_{ref}$**	**RC-C$_{min}$**	**RC-C$_{ref}$**	**RC-M$_{min}$**	**RC-M$_{ref}$**	**Mean** (across mixtures and applications)
Ecological Scarcity (MPt)	*CC Value*	2.11E+05		2.11E+05		2.02E+05		2.02E+05		
	CEM1	1.57E+05	1.27E+05	1.55E+05	1.28E+05	1.48E+05	1.18E+05	1.46E+05	1.19E+05	
	CEM2	1.61E+05	1.31E+05	1.64E+05	1.41E+05	1.52E+05	1.22E+05	1.56E+05	1.31E+05	
	CEM3	1.65E+05	1.35E+05	1.72E+05	1.53E+05	1.56E+05	1.26E+05	1.67E+05	1.44E+05	
	Mean reduction (%)	***23.46***	***37.67***	***22.33***	***33.23***	***24.57***	***39.43***	***22.41***	***34.84***	***29.8***
	SD	*1.97*	*1.98*	*3.95*	*5.11*	*2.05*	*2.04*	*5.12*	*613*	*7.9*
Ecoindicator (Pt)	*CC Value*	8.88E+00		8.88E+00		8.98E+00		8.98E+00		
	CEM1	5.96E+00	4.42E+00	6.20E+00	4.81E+00	6.05E+00	4.51E+00	6.29E+00	4.90E+00	
	CEM2	6.16E+00	4.61E+00	6.61E+00	5.41E+00	6.26E+00	4.72E+00	6.83E+00	5.54E+00	
	CEM3	6.36E+00	4.82E+00	7.00E+00	6.01E+00	6.49E+00	4.94E+00	7.37E+00	6.20E+00	
	Mean reduction (%)	***30.60***	***48.02***	***25.61***	***34.59***	***30.18***	***47.43***	***23.94***	***38.20***	***35.4***
	SD	*2.25*	*2.27*	*4.46*	*6.99*	*2.42*	*2.39*	*6.00*	*7.21*	*9.9*
GWP (kg CO_2 eq.)	*CC Value*	2.47E+02		2.47E+02		2.28E+02		2.28E+02		
	CEM1	2.23E+02	2.10E+02	2.26E+02	2.16E+02	2.04E+02	1.91E+02	2.08E+02	1.97E+02	
	CEM2	2.30E+02	2.18E+02	2.42E+02	2.39E+02	2.11E+02	1.99E+02	2.26E+02	2.20E+02	
	CEM3	2.38E+02	2.25E+02	2.57E+02	2.61E+02	2.18E+02	2.06E+02	2.45E+02	2.42E+02	
	Mean reduction (%)	***6.68***	***11.78***	***2.07***	***3.25***	***7.32***	***12.83***	***0.79***	***3.74***	***6.0***
	SD	*3.05*	*3.05*	*6.11*	*9.15*	*3.24*	*3.24*	*8.10*	*9.72*	*6.9*
ADP (kg Sb eq.)	*CC Value*	6.83E-01		6.83E-01		5.92E-01		5.92E-01		
	CEM1	4.64E-01	3.49E-01	5.06E-01	4.11E-01	3.73E-01	2.57E-01	4.14E-01	3.19E-01	
	CEM2	4.82E-01	3.67E-01	5.42E-01	4.65E-01	3.89E-01	2.73E-01	4.55E-01	3.67E-01	
	CEM3	5.00E-01	3.85E-01	5.79E-01	5.20E-01	4.05E-01	2.89E-01	4.95E-01	4.16E-01	
	Mean reduction (%)	***29.31***	***46.22***	***20.52***	***31.82***	***34.30***	***53.81***	***23.20***	***37.93***	***34.6***
	SD	*2.66*	*2.67*	*5.34*	*7.99*	*2.75*	*2.72*	*6.85*	*8.20*	*11.5*

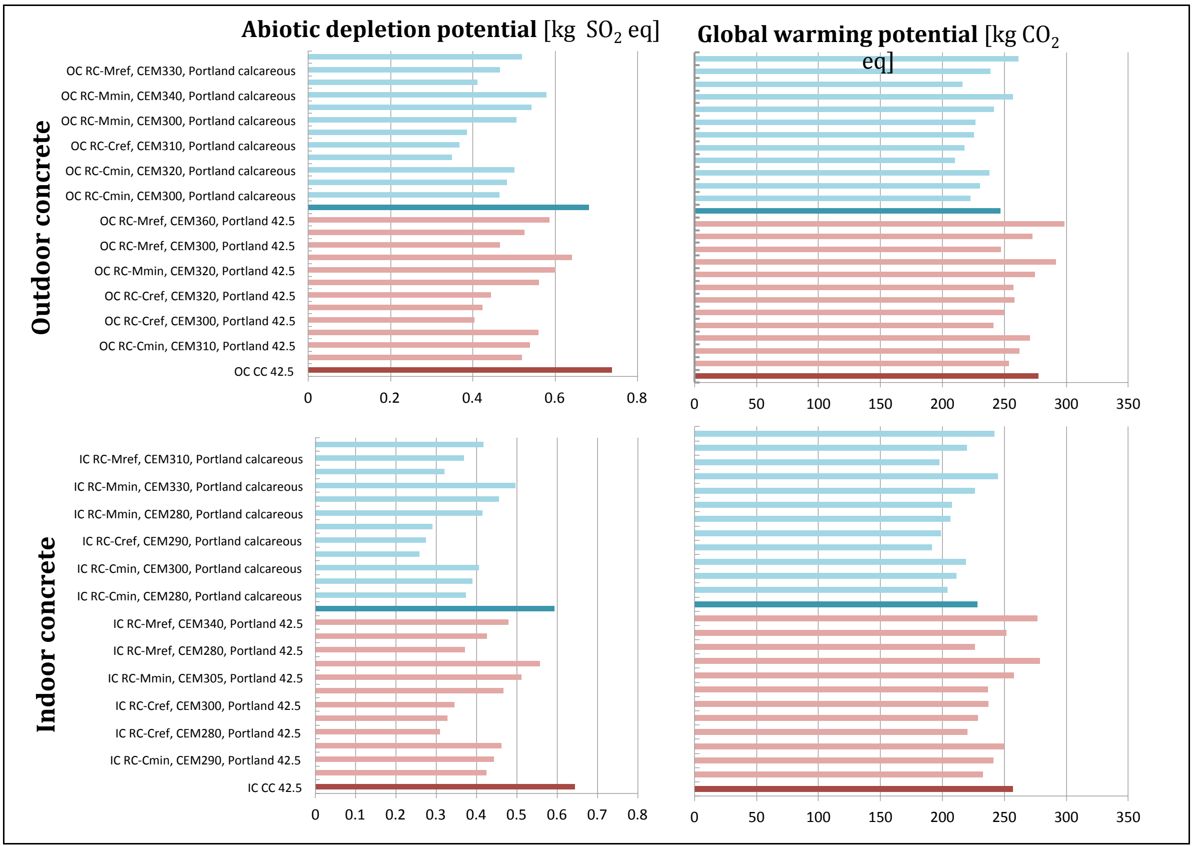

Fig. 1 Structural concrete abiotic depletion potential (ADP) [kg SO_2 eq / m^3 concrete] and global warming potential (GWP) [kg CO_2 eq / m^3 concrete] of recycling and conventional concrete mixtures (dark coloured bars indicate CC, light coloured bars RC mixtures, blue bars indicate concrete mixtures with Portland cement calcareous and red bars mixtures with Portland 42.5.

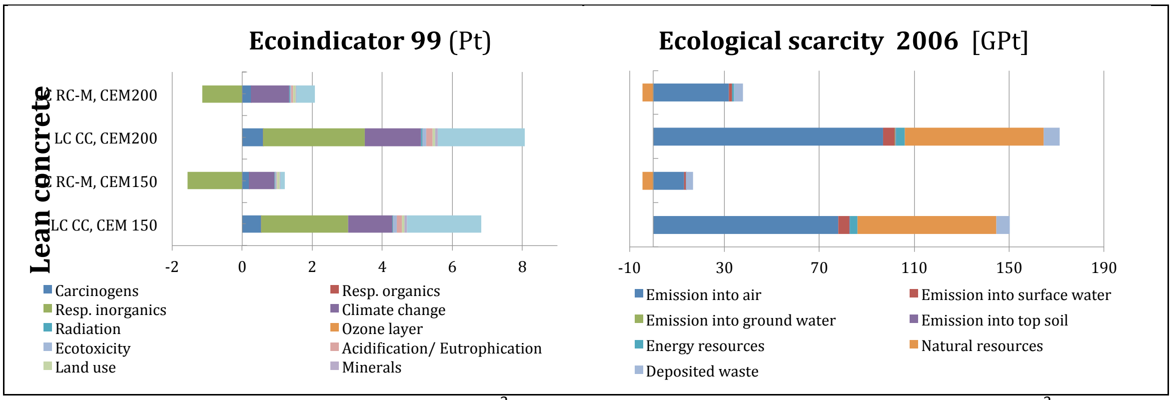

Fig. 2 Lean concrete ecoindicator 99 [Pt / m^3 concrete] and ecological scarcity 2006 [GPt / m^3 concrete] endpoint results for recycling and conventional concrete mixtures (Midpoint impacts are colour indicated for each of the two impact assessment methods)

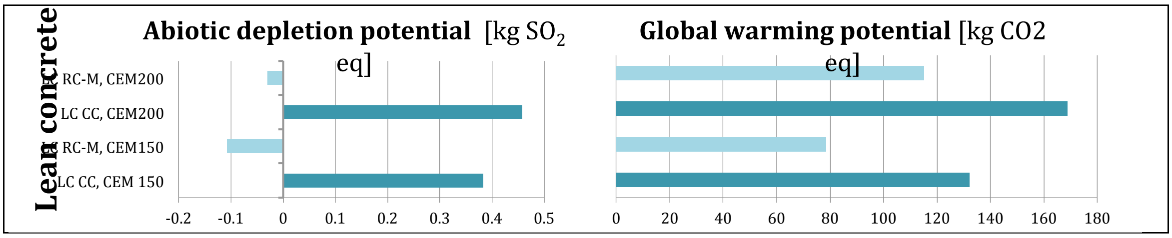

Fig. 3 Lean concrete abiotic depletion potential (ADP) [kg SO_2 eq / m^3 concrete] and global warming potential (GWP) [kg CO_2 eq / m^3 concrete] of recycling and conventional concrete mixtures (dark blue colour bars indicate CC, light blue coloured bars RC mixtures)

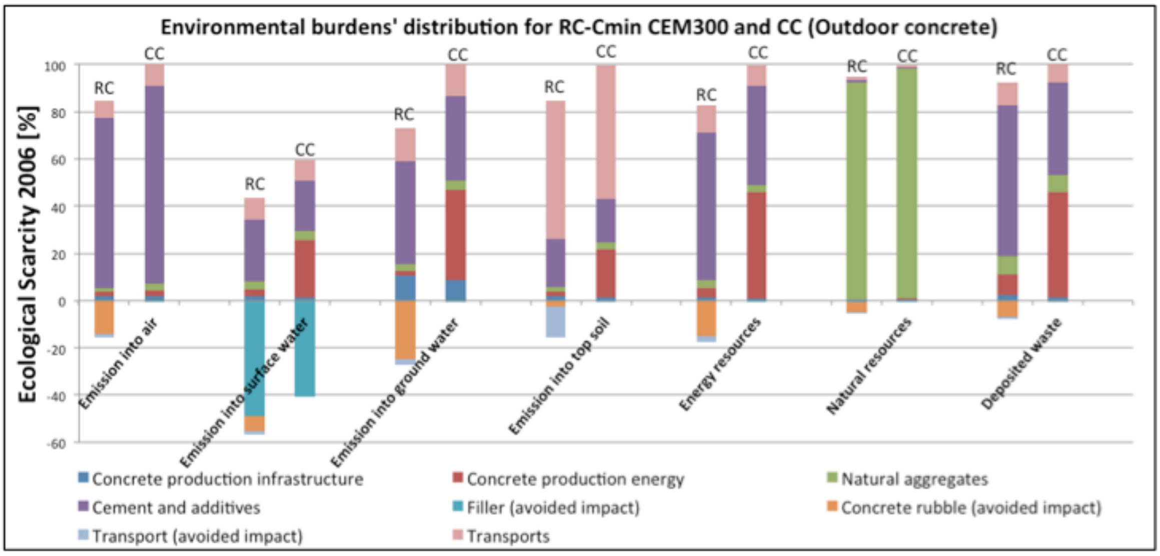

Fig. 4 Comparison of the environmental burdens' distribution of one RC-C mixture (OC RC-Cmin, CEM300, Portland 42.5) with the corresponding CC mixture (OC CC, Portland 42.5), for Ecological Scarcity 2006 midpoints. (To eliminate the influence of the cement and transport, mixtures having the same amount and type of cement have been chosen and transport distances were kept to the reference scenario)

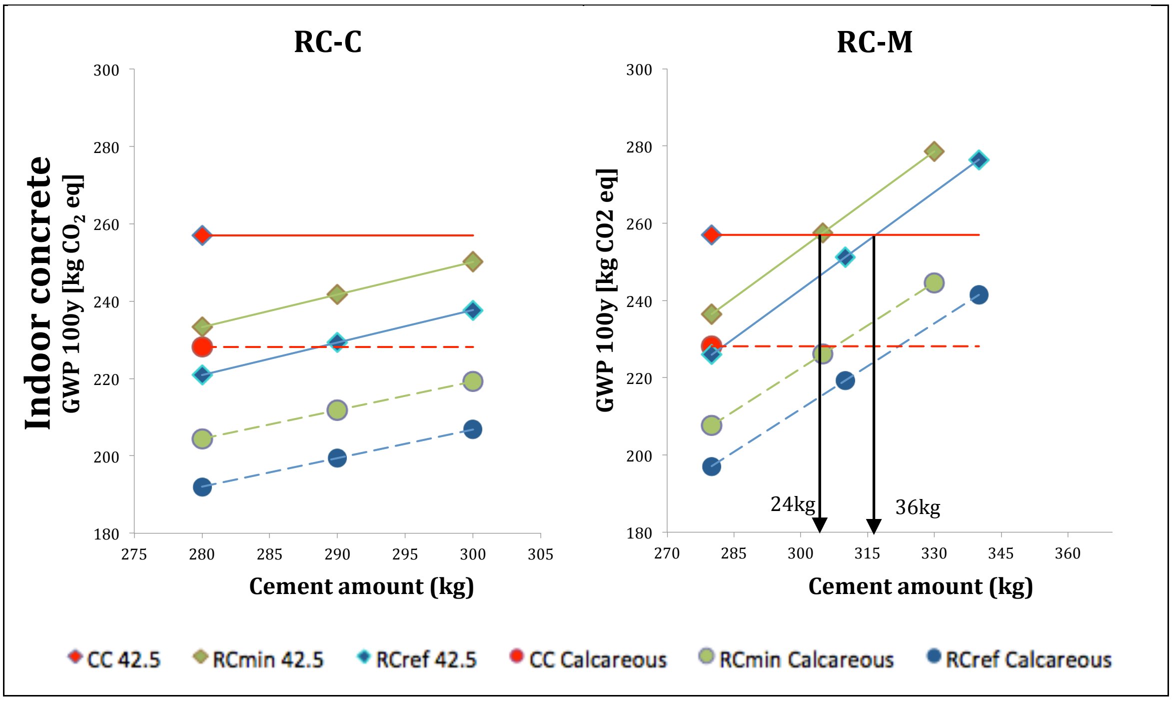

Fig. 5 Indoor concretes' GWP [kg CO_2 eq / m^3 concrete] sensitivity to additional cement content for recycling concrete (RC) (solid lines and rhomboid markers indicate concrete mixtures with Portland cement 42.5 and dotted lines and circled markers indicate concrete with calcareous cement)

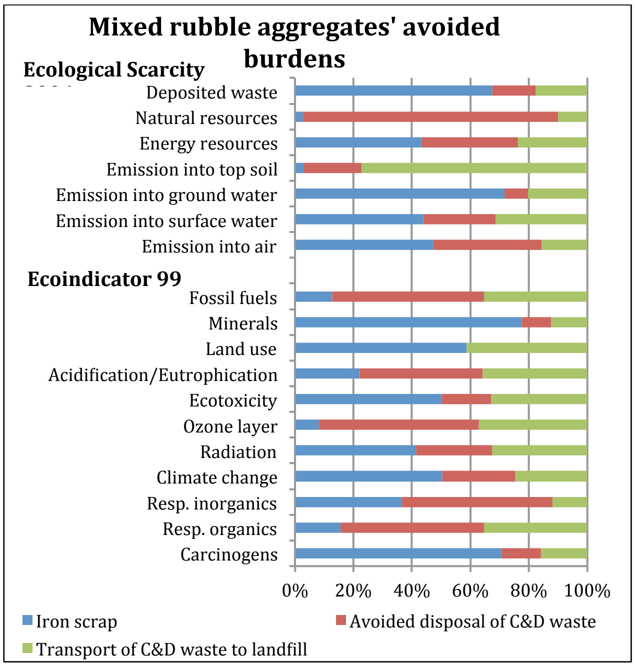

Fig. 6 Avoided burden contributions to mixed rubble aggregates from C&D waste for ecoindicator 99 and ecological scarcity 2006 midpoints

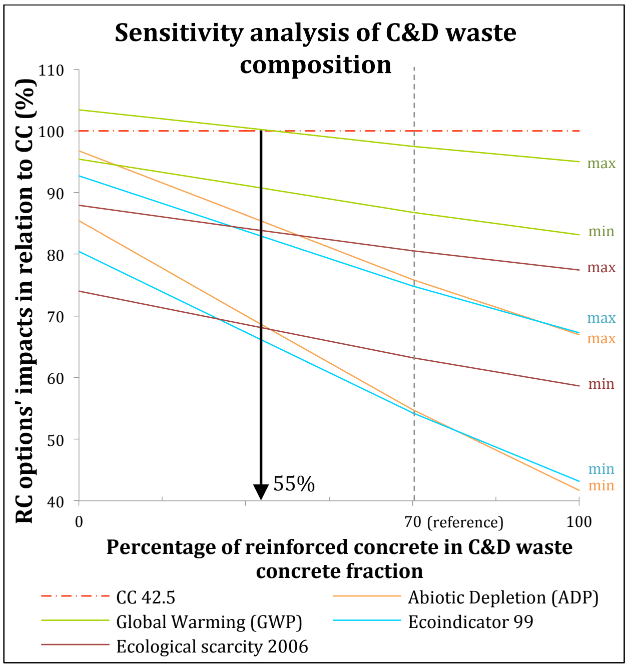

Fig. 7 Sensitive analysis of the variation of the percentage of reinforced concrete fraction in the C&D waste composition for RC-C outdoor concrete options (OC RC-Cmin 320 (max) and OC RC-Cref 300 (min) mixtures showed maximum and minimum values, respectively, delimiting the range of variation.)

Fig. 7: Sensitivity analysis of C&D waste composition: We analysed the best (OC RC-Cref 300) and worst (OC RC-Mmin 320) performing mixture with 0%, the reference scenario 70%, and 100% of reinforced concrete in the C&D waste concrete fraction and compared the results with CC at endpoint level. For excluding transport, cement type and application effects, we compared reference transport distances and mixtures with Portland 42.5 cement for outdoor concrete.

Except for GWP all RC mixtures indicators show lower environmental impacts than CC. The worst RC mixture has equal GWP at 55% reinforced concrete in the C&D waste concrete fraction; at reference C&D waste composition this RC mixture still causes slightly lower GWP than CC.

Fig. 8: Comparison of RC with an iron scrap extraction system: The "iron scrap extraction" system assumes C&D waste treatment similar to the recycling system but without utilization of the mineral fraction. The system includes dismantling, sorting and crushing of C&D waste and the avoided burdens from recovered steel scrap, but not avoiding the burdens of C&D waste landfilling. We compared RC-C mixtures with Portland 42.5 cement for outdoor concrete applications with reference transport distances. Because of different amounts of aggregates substituted in the RC-C mixtures (i.e. min 28%, ref 45%), two CC iron extraction systems have been analysed, one each with the corresponding amount C&D waste for iron extraction. Fig. 8 shows the results for abiotic depletion potential (ADP) and global warming potential (GWP 100y), as midpoints, and ecological scarcity 2006 (EC 2006) and ecoindicator 99 (EI 99), as endpoints. The comparison show clear environmental benefits for EC 2006, EI99 and ADP, while for GWP RC-C mixtures and the CC iron extraction system are on the same level. Again, the more aggregates substituted the better the environmental performance of RC-C mixtures.

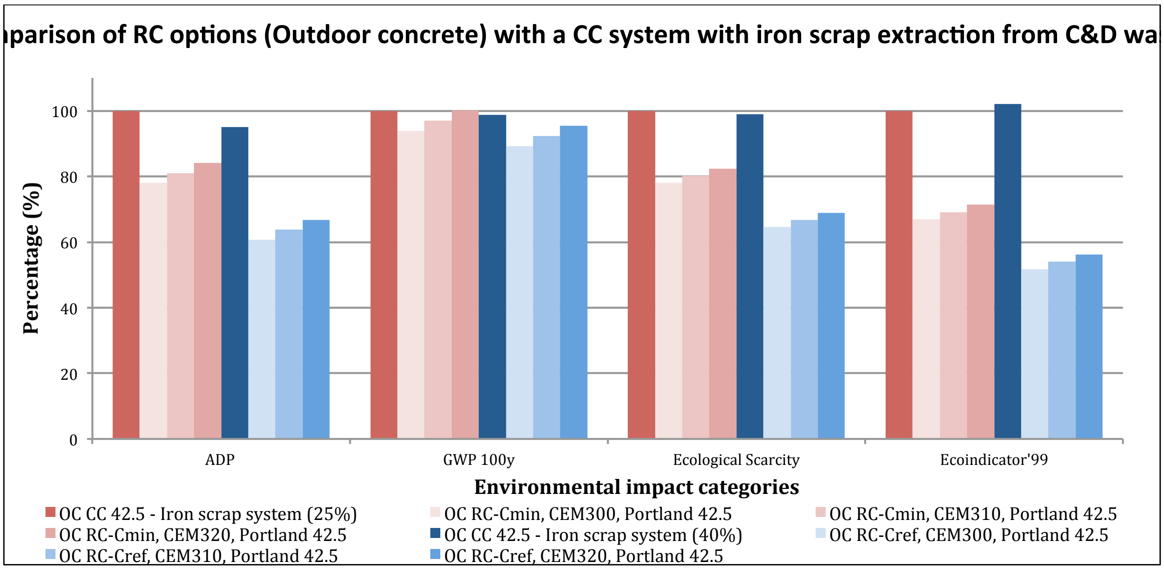

Fig. 8 Comparison of RC-C option for outdoor concrete with a CC system with iron scrap extraction from C&D waste for abiotic depletion potential (ADP) and global warming potential (GWP 100y), as midpoints, and ecological scarcity 2006 and ecoindicator 99, as endpoints (dark coloured bars indicate CC, light coloured bars RC mixtures, red bars indicate mixtures with minimal and blue bars mixtures with reference aggregates substitution)

Short Curriculum Vitae

Christof Knoeri

	Born: 10.01.1977 Worb,
	Swiss National

Education

2007 - 2014	PhD in Geography Department of Geography, University of Zurich, Switzerland
2001 - 2007	MSc in Environmental Science Department of Environmental Science, ETH Zurich, Switzerland

Employment

2012 - present	Research Fellow at the Sustainability Research Institute, University of Leeds, UK
2011 – present	Visiting Lecturer and Research Assistant at the Chair of Human-Environment Relations, University of Munich, Germany
2009 – 2012	Guest Lecturer at the Institute for System Sciences Innovation and Sustainability Research, University of Graz, Austria
2007 – 2011	Research Assistant at the Technology and Society Laboratory, EMPA Material Science and Technology, Duebendorf, Switzerland
2007 – 2011	Research and Teaching Assistant at the Social and industrial Ecology Unit at the Department of Geography, University of Zurich, Switzerland
December 2009	Research stay at the Faculty of Technology, Policy and Management, Delft University of Technology, The Netherlands
2005 – 2006	Project Manager at CHAL, Christian Health Association Lesotho, Maseru, Lesotho
1993 – 1997	Apprenticeship as Construction Draftsman at the Vocational Collage for Business and Industry, GIB Thun, Switzerland and GAL Architects, Heimberg Switzerland

Personal bibliography

Peer reviewed journal publications

Knoeri, C., Binder, C. R., & Althaus, H. J. (2011). *An agent operationalization approach for context specific agent-based modelling.* JASSS The Journal of Artificial Societies and Social Simulation, 14(2).

Knoeri, C., Binder, C. R., & Althaus, H. J. (2011). *Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials.* Resources, Conservation and Recycling, 55(11), 1039-1050.

Knoeri, C., Sanyé-Mengual, E., & Althaus, H. J. (2013). *Comparative LCA of recycled and conventional concrete for structural applications*. International Journal of Life Cycle Assessment, 18(5), 909-918.

Knoeri, C., Wäger, P. A., Stamp, A., Althaus, H. J., & Weil, M. (2013). *Towards a dynamic assessment of raw materials criticality: Linking agent-based demand - with material flow supply modelling approaches.* Science of The Total Environment, 461-462, 808-812.

Knoeri, C., Nikolić, I., Althaus, H. J., & Binder, C. (2014). *Enhancing recycling of construction materials: the role of empirically based decision parameters.* JASSS The Journal of Artificial Societies and Social Simulation, 17(3) 10.

Roelich, K., Dawson, D., Purnell, P., **Knoeri, C**., Revell, R., Busch, J., & Steinberger, J. K. (2014). *Assessing the dynamic material criticality of infrastructure transitions: a case of low carbon energy generation.* Applied Energy, 2.

Roelich, K., **Knoeri, C**., Steinberger, J. K., Varga, L., Blythe, P. T., Butler, D., et al. (forthcoming). *Towards resource-efficient and service-oriented integrated infrastructure operation.* [accepted for publication] Technological Forecasting and Social Change.

Knoeri, C., Steinberger, J. K., & Roelich, K. (forthcoming). *End-user centred infrastructure operation: towards integrated infrastructure service delivery.* [accepted for publication] Journal of Cleaner Production.

Peer reviewed conference publications

Roelich, K., Steinberger, J. K., & **Knoeri, C.** (2013). *Efficient and service oriented infrastructure operation: the role of the Energy Efficiency Directive in driving change towards Multi-Utility Service Companies.* Paper presented at the ECEEE 2013 Summer Study on Energy Efficiency.

Knoeri, C., Goetz, A., & Binder, C. R. (2014). *Generic bottom-up building-energy models for developing regional energy transition scenarios*. Paper to be presented at the 9th Conference of the European Social Simulation Association, Barcelona, Spain

Non-peer reviewed and other publications

Knoeri, C. (2006). *Anwendungen von Agenten basierter Modellierung im Umwelt- und Ressourcen-Management.* Unpublished Semesterarbeit, ETH Zurich, Zürich.

Knoeri, C. (2007). *Agent based modelling (ABM) for analysing demand for recycled mineral construction material* Unpublished Diploma Thesis, Swiss Federal Institute of Technology ETH, Zürich.

Binder, C., **Knoeri, C.**, & Weager, P. (2008). Simulation of socio-ecological transitions with Agent Based Modelling: From real systems to conceptual models. *Workshop position paper for the International Congress on Environmental Modelling and Software.*

Steinberger, J. K., Roelich, K., & **Knoeri, C**. (2013). *Shaking up Infrastructure: Land of the MUSCos.* International Innovation; Disseminating Science, Research and Technology.

Knoeri, C., Althaus, H. J., & Binder, C. (2013). *Entscheidungsgrundlagen & Empfehlungen für ein nachhaltiges Baustoffmanagement; Schlussbericht zum ASTRA Forschungsauftrag 2005/004:* Bundesamt für Strassen ASTRA, Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK.

Supervised and co-supervised Master-, Semester-, and Bachelor thesis

Barras, I. (2009). *Recycled construction materials in Romandie.* Unpublished Master Thesis, Swiss Federal Institute of Technology (ETH) Zurich.

Vorderman, D. (2009). *Integrative Evaluation des Brockenhauses Zug anhand der Kombination des St.*

Galler und Freiburger Management-Modells; Mit dem Fokus auf die Mitarbeitenden. Unpublished Materthesis, University of Zurich.

Hool, A. (2010). *Verwertung mineralischer Baustoffe; Rolle der kantonalen Vorschriften [Mineral construction material recycling; the role of cantonal regulation].* Unpublished Semester Thesis, Swiss Federal Institute of Technology (ETH) Zurich.

Preinknoll, C. (2011). *Kritikalität von knappen Metallen: Vergleich der Indikatoren [Criticality of scarce metals: Comparison of indicators].* Unpublished Bachelor Thesis; Karl-Franzens-Universität Graz.

Conference presentations

Knoeri, C., Binder, C. R., & Althaus, H. (2007, August 27 to 29, 2007). *Agent based modelling (ABM) for analysing the demand for recycled mineral construction material.* Paper presented at the LCM 2007, 3rd International Conference on Life Cycle Management Zurich, University of Zurich Irchel.

Knoeri, C., Binder, C. R., & Althaus, H. (2007, September 3rd to 5th, 2007). *Agent based modelling (ABM) for analysing the demand for recycled mineral construction material.* Paper presented at the R'07 World Congress Recovery of Materials and Energy for Resource Efficiency, Davos Congress Centre, Switzerland.

Knoeri, C., Binder, C. R., & Althaus, H. J. (2008, 17-22 August 2008). *Decision support and recommendations for a sustainable construction material management.* Paper presented at the Industrial Ecology Conference, Colby-Sawyer College, New London, NH.

Knoeri, C., Binder, C., & Althaus, H. J. (2009, 06.22.2009). *Integrated agent-based decision-making modelling and spatially explicit material flow simulation; The Swiss recycling construction material market.* Paper presented at the 2009 International Society for Industrial Ecology Conference; Transition towards Sustainability, Lisbon.

Knoeri, C., Binder, C., & Althaus, H. J. (2009, 09.08.2009). *Empirical operationalized decisions for agent based modelling; Swiss recycling construction material usage.* Paper presented at the 8th Biennial Conference on Environmental Psychology, Zürich.

Knoeri, C., Binder, C., & Althaus, H. J. (2011, 19.-21.09.2011). *How interacting agents affect resources; Demand for recycled mineral construction materials in Switzerland.* Paper presented at the 2011 World Resource Forum; Shaping the Future of Natural Resources - Towards a Green Economy, Davos, Switzerland.

Knoeri, C., Wäger, P. A., Stamp, A., & Althaus, H. J. (2011). *From static to dynamic criticality assessment: Linking agent-based modelling with material flow modelling approaches*. Paper presented at the 2011 International Society for Industrial Ecology Conference; Science, Systems and Sustainability.

Knoeri, C., Wäger, P. A., Stamp, A., Althaus, H. J., & Weil, M. (2011, 19.-21.09.2011). *Towards a dynamic criticality assessment: Linking agent-based demand - with material flow supply modelling approaches.* Paper presented at the 2011 World Resource Forum; Shaping the Future of Natural Resources - Towards a Green Economy, Davos, Switzerland.

Knoeri, C., Steinberger, J. K., Roelich, K., & Varga, L. (2012, June 17-22). *Resource-efficient and service-oriented infrastructure operation: towards MUSCos: Multi-Service Utility Companies* Paper presented at the GRC Industrial Ecology: "The Role of Industrial Ecology in Addressing Sustainability Imperatives", Les Diablerets, Switzerland.

Varga, L., **Knoeri, C**., Steinberger, J. K., Roelich, K., & Varga, S. (2012, July 2-4). *Modelling transitions towards resource-efficient and service-oriented infrastructure operation.* Paper presented at the International Workshop on Agent-Based Models and Complex Techno-Social Systems, ETH Zurich, Switzerland.

Binder, C., Watts, C., & **Knoeri, C**. (2012, September 10 – 14). *Modelling the humans in social-ecological systems.* Paper presented at the ESSA 2012 – 8th Conference of the European Social Simulation Association, University of Salzburg, Austria

Knoeri, C., Roelich, K., Steinberger, J. K., & Varga, L. (2012, September 18-19). *Resource efficient and service oriented infrastructure operation: Towards MUSCos: Multi-Utility Service Companies.* Paper presented at the ARCC CN Conference, 2012 Living with our Buildings and Infrastructure: Adapting for the Future, Birmingham, UK.

Knoeri, C., Steinberger, J. K., Roelich, K., & Varga, L. (2012, November 27). *Resource-efficient and service-oriented infrastructure operation: towards MUSCos: Multi-Service Utility Companies* Paper presented at the ITRC Early career Researcher Conference, Cambridge University, UK.

Roelich, K., Steinberger, J. K., **Knoeri, C**., & Schmieder T. (2012). *Resource efficient and service oriented infrastructure operation: The role of Multi-Utility Service Companies in driving change towards SCP.* Paper presented at the Innovation for Sustainable Production, Bruges.

Roelich, K., Schmieder T, Steinberger, J. K., & **Knoeri, C**. (2012, November 5-6). *Resource-efficient and service-oriented infrastructure operation: The role of Multi-Service Utility Companies in driving change towards sustainable and resilient urban infrastructure systems.* Paper presented at the 1st International Conference on Urban Sustainability and Resilience, University College London.

Knoeri, C., Steinberger, J. K., & Roelich, K. (2013, June 25-28). *Infrastructure as though the end-user matters; from utility products to infrastructure services.* Paper presented at the International Conference on Industrial Ecology: Strategy for Green Economy, Ulsan, South Korea.

Knoeri, C., Steinberger, J. K., Roelich, K., & Schmieder, T. (2013, July 3-4). *Infrastructure as though the end-user matters; from utility products to infrastructure services.* Paper presented at the International Symposium on Modelling Sustainable Urban Transition Dynamics, Cardiff, UK.

Binder, C. R., **Knoeri, C.,** Hecher, M., Kislinger, M., Vilsmaier, U., Kreuzeder, A. (2014, June 4-6) *Sequence of transition pathways in energy transitions: the need for understanding technology acceptance, and developing common visions.* Paper presented at the 2nd Energy & Society Conference, Krakow, Poland.

Roelich, K., **Knoeri C.,** (2014, June 10-11) *Towards resource-efficient integrated infrastructure services: The role of end-users and policy.* Paper presented at the ARCC Network Assembly, Birmingham, UK.

Acknowledgments

As many people contributed to and supported me during the journey leading to the completion of this thesis, I am highly likely going to miss some of them in my acknowledgements. Therefore, my thanks go to everybody who contributed to this endeavour, but in particular to the following:

My two main supervisors Claudia R. Binder and Hans-Joerg Althaus, without their encouragement I probably never entered research, for the challenging discussions, the freedom to go astray at times, and the patience they had with me to get back on track.

Michael Schaepman for leading the committee and his support in the final steps.

Patrick Wäger and Holger Wallbaum for providing their expertise in the dissertation committee.

Anna Stamp, Andrea Delduce, Bernhard Steubing, Dominik Notter, Jürgen Reinhard, Marloes Caduff-Kinkel, Martin Lehmann, Rainer Zah, and Simon Gmünder at the former Life Cycle Assessment and Modelling Group at EMPA Materials Science and Technology, for making it an really inspiring work environment.

Giuseppe Feola and Regina Schoell at the former Social and Industrial Ecology Group at University of Zurich, for sharing office and all the inspiring discussions.

Igor Nikolic and Chris Davis at TU Delft for introducing me to the world of modelling and an inspiring month in Delft.

Julia Steinberger at the Sustainable Research Institute at the University of Leeds for giving me the opportunity to finish this thesis while being on the new job, and Katy Roelich & Jonathan Busch for sharing office and being supportive in the final steps.

Irène Barras and Esther Sanye for contributing to this work with their master thesis and internship respectively.

Experts of the project advisory board for providing their support, time, and knowledge in various workshops and meetings.

FEDRO (Swiss Federal Roads Office), FOEN (Federal Office for the Environment), AWEL (Amt für Abfall, Wasser, Energie und Luft; Environmental Agency) of canton Zurich, AHB (Amt für Hochbauten; Office for structural engineering) of the City of Zurich and Eberhard Recycling AG for funding the study.

My parents and family for all their support during my studies

to Sonja for being at my side